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HYDRAULIC LIME MORTARS

Peter Thomas Ellison

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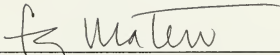
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Introduction

Hydraulic lime mortars were, during the nineteenth century, a widely used material in Europe, Great Britain, and to some extent North America. Recently, hydraulic lime mortars have been rediscovered by the conservation/restoration community as potential substitutes for lime and cement-lime formulations. Hydraulic limes show great potential in restoration by having some of the advantageous properties of Portland cement as well as those of high calcium lime putty. In the first half of this study the constituents, properties, manufacturing, and uses of hydraulic lime are examined. In the second half of the document, three commercially available hydraulic hydrated limes that are currently available in North America are tested and reviewed, with the aim of establishing their properties and possibilities for their use. The intent of this paper is to establish what hydraulic limes are and investigate how they might be used in the conservation and restoration of traditional and aged masonry.

Hydraulic lime formed an important part of masonry history. From the work of John Smeaton in the mid eighteenth century, to L.J. Vicat in the nineteenth century, and as late as the 1950s, many treatises on masonry recognize the importance of hydraulic limes in the context of mortar and plaster formulations. Before Portland cement came into widespread use, hydraulic lime and natural cements were the chief hydraulic materials. By the end of the nineteenth century Portland cement was readily available and significantly reduced the use of hydraulic lime but not natural cements.¹ The first Portland cement factory was built in the United States in 1872, with 82,000 barrels produced in eight years. In 1890 the production of Portland cement was 335,000 barrels from sixteen factories, and by 1903 production had increased to 22,342,973

¹ John Ashurst, "The Technology and Use of Hydraulic Lime," *The Building Conservation Directory 1997*, Fifth Edition, (Wiltshire, England: Cathedral Communications Limited, 1997), p.128.

barrels from seventy-eight factories.² For over half a century these materials, which were once a major part of masonry construction, were eclipsed. For certain types of work these limes were, and still are, the most appropriate material to use. The beneficial effects of hydraulic lime mortar include good water retention, good workability, good water tight bond with masonry, small cyclic volume changes, a quicker set than lime putty mortars, good vapor transmission rates, good strength, and low harmful impurity content, etc. In general, it displays the most favorable properties of both lime putty and Portland cement.

Definition

English Heritage defines non-hydraulic limes (air-limes, fat-limes or high-calcium limes, dolomitic-limes) as those which do not set in water but require carbon dioxide in air in order to harden. Typically they are produced from limestone which is a relatively pure source of calcium carbonate (CaCO_3). English Heritage believes that traditionally made lime putty should be used whenever possible because of its “superior plasticity and binding powers”.³

Hydraulic limes are those which set by a chemical reaction with water and so differ from non-hydraulic limes. They are capable of setting and hardening under water. The raw material for hydraulic lime is limestone, but it is an argillaceous or siliceous limestone which contains calcium and magnesium carbonate. These limestones yield a hydraulic lime after calcination. Hydraulic limes have traditionally been classified by the amount of re-active clay material they contain. They are divided into three subdivisions which are based on their hydraulicity or setting time. The three subdivisions are feebly-hydraulic, moderately-hydraulic, and eminently-

² G.P. Grimsley and I.C. White, "Clays, Limestones, and Cements," *West Virginia Geological Survey*, Volume Three, (1905), p. 425.

³ English Heritage, "Hybrid Mortar Mixes Containing a Blend of Both Non-Hydraulic Lime and Hydraulic Lime Binders," *English Heritage Technical Policy Statement*, Product Code XH20061 (May, 1997), p.1.

hydraulic. Eminently-hydraulic limes set quicker and obtain higher compressive strengths than feebly-hydraulic limes, with moderately-hydraulic limes falling in between the two.⁴ The relative quantities of a lime's constituents determine its degree of its hydraulicity. These hydraulicity classifications are somewhat arbitrarily based. Two limes of similar chemical composition may show entirely different strength development and setting times. The usual chemical analysis does not indicate the difference in the hydraulic properties of two limes with similar chemical compositions but different physical natures.⁵

All commercially available hydraulic limes come in the form of a dry powder hydrate. The material must be sealed and be stored in a dry place, because moisture can initiate the setting process and cause the binder to lose some or all of its setting properties. Typically they should be used within six months to a year. There are a number of hydraulic limes available in Europe and a few available in North America and in the United Kingdom. The properties of the hydraulic limes depend on their composition and the burning and slaking specification. It is essential to know this information when hydraulic lime is to be used. In addition, manufacturers and suppliers should make known the chemical analysis of their material and any other production data.⁶

Constituents

The properties of hydraulic limes depend on their chemical composition, the manner in which they have been burned, and on the manner they have been slaked or hydrated. The composition of hydraulic limestone includes the amount and types of inorganic impurities which

⁴ Ibid.

⁵ Mohan Rai, "Hydraulic Lime," *Journal of Scientific and Industrial Research*, Volume 23, 1964, pp. 376-8.

⁶ Ashurst, "Technology and Use of Hydraulic Lime," p.129.

give the hydraulic lime its hydraulicity. These impurities include silica, alumina, and ferric oxide.

As early as 1872 Burnell stated

One law is, however, certain; namely, that no limestones are able to produce, in a commercially valuable form, hydraulic limes, unless silica be present in combination with alumina. It may be regarded as the most efficient agent in producing the power of setting under water; and being the one whose presence should be sought for, and supplied if wanting, whenever it is desired to obtain limes of that description.⁷

Silica (silicon dioxide, SiO_2) is found in the majority of natural rocks, most often in the less impure forms of quartz and feldspars. Silica of this form is very stable. Other forms of silica are mainly finely-divided, water-containing varieties such as diatomaceous earth, which consists of weathering residues of minute siliceous skeletons of aquatic plants called diatoms. Because of their fine state of sub-division, these forms of silica are far more reactive than ordinary quartz. When heated to a high temperature, even ordinary quartz silicon can become chemically reactive. In addition, strong alkalis react with quartz at a high temperature to give a water-soluble product.⁸

The formation of colloidal compounds from lime, silica, and water (calcium silicate hydrates or calcium hydrosilicates) are the most important factors in the phenomenon of hydraulic hardening. Colloids are substances that are characterized by large surface areas. They consist of a dispersed matter (can be any matter) in a given medium. The word colloid is derived from the Greek word "kolla", which means glue. Hydraulic hardening depends on the formation of these "mineral glue" substances. The process of hydraulic hardening (reaction of calcium oxide and silica) is similar to the process used in the manufacture of water glass, which is a

⁷ Burnell, *Rudimentary Treatise on Limes*, p. 19.

silica-containing aqueous solution. Calcium oxide and silica have very limited solubility in water, but, when two solutions containing lime and silica are mixed together they form a precipitate. This precipitate forms a gel-like material which has good tensile strength and cohesiveness. Calcium silicate hydrates, or calcium hydrosilicates are by far the most important compounds in the phenomenon of hydraulic hardening.⁹

Alumina is similar to silica in that it reacts with the lime and water to give a gel-like substance. In chemical terms alumina is pure aluminum oxide (Al_2O_3). Clay contains a large portion of alumina. Kaolinite clay is composed of alumina, silica and water in the following proportions: 46.5% silica (SiO_2), 39.5% alumina (Al_2O_3), and 14.0% water (H_2O). The mineral kaolinite is the main constituent of kaolin. The chemical composition of mineralogical clays is generally such that the silica content is twice as high as the sum of the content of alumina and ferric oxide, - similarly the alumina is twice the content of the ferric oxide. The colloidal hydrated-compounds of calcium oxide and alumina, play a less important roll in hydraulic hardening than the calcium hydro silicates.

Ferric oxide is contained in smaller or larger amounts in most minerals and especially in clays. Therefore it is almost unavoidable that it is present in hydraulic-cements. Iron behaves as a fluxing agent in the process of clinker-burning; facilitating the formation of the chemical compounds forming the basis of cement manufacture at a much lower temperature than would be possible otherwise.¹⁰

⁸ F.M. Lea, *The Chemistry of Cement and Concrete*. Third Edition, Edward Arnold Publishers Ltd. London, 1962, p. 3.

⁹ *Ibid.*, p. 9.

¹⁰ *Ibid.*, pp. 7-8.

The properties of hydrated hydraulic lime can be compared to those of a mixture of Portland cement with a corresponding proportion of hydrated lime. The material is easy to use and flows freely under the trowel, but sets and hardens more slowly than Portland cement and does not attain as great a strength as a lime-free Portland mix.¹¹

The hydraulic limes with high compressive strength contain 65% lime, 10 - 12% alumina, and 23 - 25% silica, which approximates the same proportions as a typical Portland cement. The setting of hydraulic lime is a similar process to that of Portland cement, but because there is less free lime in Portland cement, more strength is produced in the Portland.¹²

Use of Lime and Hydraulic Lime

The uses of lime and hydraulic lime mortar mixes depend on the exposure, weathering, and/or frost action a structure or area will receive. The use of a non-hydraulic or feebly-hydraulic lime is totally acceptable to use and its use is encouraged, but it is not suited for areas that are exposed, - such as chimneys, copings, wall-heads, weatherings, quoins or paving. In addition, these limes must not be installed nor cured during frost-prone periods. The durability of these limes can be improved by the addition of a pozzolanic material like low-fired, fine ceramic powder, but their general limitations still apply. Ashurst maintains that a mature lime putty is often the perfect material for conservation; because of its sacrificial nature, consistency, water retention, and compatibly for weakened and weathered masonry.

There are several limitations or disadvantages to using lime putty mortars. Lime putty mortars require the use of a mortar mill or hand ramming for optimum performance; lime putty

¹¹ Alfred B. Searle, *Limestone and Its Products, Their Nature, Production, and Uses*, (London: Ernest Benn Limited, 1935), p. 571.

¹² N.V.S. Knibbs, *Lime and Magnesia, The Chemistry Manufacture and Uses of the Oxides, Hydroxides and Carbonates of Calcium and Magnesium*, (New York: D. Van Nostrand Company, 1924), pp. 243-4.

mortar is slow setting and curing; lime putty mortars are moisture sensitive during curing; and lime putty mortars should cure for twenty-eight days before exposure to frost. In general, lime putty mortars are more labor intensive, "fickled", and therefore more costly than a hydraulic hydrated lime mortar. Hydraulic hydrated lime does not need to be slaked; does not need a mortar mill or to be rammed; is quicker setting and can be exposed much sooner to frost; and the material costs less and is less labor intensive.

Feebly to moderately-hydraulic limes are building limes that are suited to greater exposure than the non-hydraulic to feebly-hydraulic limes. Limes in this category tend to have a buff or a pale cream color and are relatively plastic and workable. Properly mixed, placed and cured, they have great versatility, but should not be used in very demanding exposures such as copings, chimneys and pavings. Their initial setting time varies between four and twelve hours.

Moderately to eminently-hydraulic limes are traditionally burned to form a clinker, ground, and slaked (hydrated). They may contain pozzolanic additives to bring them to a standard, such as white Portland cement (some French imports) or volcanic ash (some Italian imports). The limes should be stored dry and should not be in excess of six months old. Ashurst recommends the mixing of hydraulic lime mortars by an air-entraining process. A spiral-blade drum mixer or a whisk mixer are said to be ideal. Ten to fifteen minutes mixing should be interrupted for five minutes to let the mix stand.¹³

Moderately to eminently-hydraulic limes have great versatility and may be used on copings, chimneys, weatherings and pavings, as well as for bedding ashlar, rubble, and for plastering. These limes have good water vapor permeability and the ability to accommodate movement. In addition, they are salt and frost resistant. These limes were used extensively in

¹³ Ashurst, "Technology and Use of Hydraulic Lime," p.128.

engineering work and have been prized since ancient times.¹⁴ The extent of their use in North America could not be determined. Their use appears to have been less common than in Europe.¹⁵

Lime Characterization

The following chart¹⁶ classifies limes and hydraulic limes and their corresponding properties.

Lime & Cement - Classification & Properties

| Lime Classification | Active Clay Materials | Setting Time in Water | Slaking Time | Expansion |
|---|------------------------|-----------------------|--------------|------------------|
| Fat Lime - white color | < 6% (typically < 2%) | no set (putty) | very fast | considerable |
| Lean Lime - white, off-white color | < 12% (typically < 6%) | no set (putty) | fast | large (e.g. x 2) |
| Magnesian (dolomitic) - white, off-white color | typically < 10% | no set (putty) | very slow | varies |
| Feebly Hydraulic - off white, pale gray color | < 12% | < 20 days | slow | slight |
| Moderately Hydraulic - pale gray, buff color | 12 - 18% | 15 - 20 days | slow | slight |
| Eminently Hydraulic - gray brown color | 18 - 25% | 2 - 4 days | very slow | slight |
| Natural Cements - light to very dark brown color | 30 - 40% | 12 hours | very slow | slight |

based on DSIR Special Report No 9 "Lime and Lime Mortars" 1927

¹⁴ Ibid.

¹⁵ Grimsley and White, "Clays, Limestones, and Cements," p. 424.

¹⁶ Ashurst, "Technology and Use of Hydraulic Lime," based on DSIR Special Report No. 9 "Lime and Lime Mortars" 1927, p. 128.

The Geology of Hydraulic Limes

Pure lime (CaO) does not occur naturally in nature, because it adsorbs water and carbon dioxide from the atmosphere. It is found in the state of the bi-carbonate, carbonate, and sub-carbonate of lime. Commercial lime is obtained by the calcination of these carbonates; which consists of driving off the carbon dioxide by heat.¹⁷

The minerals that contain calcium and calcium-magnesium carbonate (calcite, aragonite, dolomite, magnesite)¹⁸ occur in stones that are generically referred to as “limestones” or “calcareous stones”. Their composition is basically calcium carbonate (CaCO₃), magnesia (MgO), manganese, iron oxide (ferric oxide, Fe₂O₃), silica (silicon dioxide, SiO₂), and alumina (aluminum oxide, Al₂O₃) combined in various proportions. They are also found with clay (either bituminous or not), quartzose sand, and numerous other substances.

The name limestone is generally applied to substances in the above mixtures which contain at least one-half their weight of calcium carbonate. Limestone is divided into subdivisions such as argillaceous, magnesian, siliceous, ferruginous, bituminous, etc.¹⁹ The subdivisions are further divided by varieties of form and texture, which are known under such names as lamellar, sacchroid, granular, compact, oolitic, chalky, pulverent, pseudomorphic, concerted, etc. This nomenclature is important because every type of limestone yields a lime of different quality, distinct in color and weight, its avidity for water, and especially in the degree

¹⁷ Burnell, *Rudimentary Treatise on Limes*, pp. 8-9.

¹⁸ Robert S. Boynton, *Chemistry and Technology of Lime and Limestone*, Second Edition, (New York: John Wiley & Sons, 1980), pp. 7-8.

¹⁹ *Ibid.*, pp. 9-11.

of hardness it is capable of assuming when made into a mortar. But the physical and mechanical properties of a stone are far from being a standard as to the quality of the lime it can yield.²⁰

Calcium carbonate occurs in nearly all geological formations, but it is scarce in the primary ones. It is more abundant in the transition rocks; and it constitutes the great mass of the secondary and tertiary formations. The secondary and tertiary calcareous rocks contain mixtures of clay and other ingredients which render them the most suitable to furnish building limes.²¹

Limestone is generally of organic origin, being composed of fossiliferous, marine sediments consisting of shells and skeletons of plants and animals. These shells and skeletons are almost pure calcium carbonate. These sediments were gradually deposited in layers sometimes forming massive beds of limestone. Some of the sediment was deposited naturally through the chemical reaction of the dissolution of calcium carbonate fossils. This occurred through the solvent action of carbon dioxide forming calcium bicarbonate, which was then reprecipitated in carbonate form. Direct precipitation of the carbonate through a saturated solution was caused either by an increase in temperature or evaporation.²²

Generally massive limestone beds are the purest, and can be hundreds of feet thick. Usually the deposit has impurities such as silica that become a part of the stone, apparently cemented to the carbonate particles. Frequently thick beds of pure limestone are divided by strata of impure stone. If a limestone is impure, contamination generally occurs with soil at the beginning of its deposition. Limestone can also become contaminated by absorption through

²⁰ Burnell, *Rudimentary Treatise on Limes*, pp. 9-10.

²¹ Ibid.

²² Robert S. Boynton, *Chemistry and Technology of Lime*, p. 5.

pores during deposition. The impurities may occur laterally as well as vertically through a limestone bed.²³

The limestones likely to yield hydraulic limes occur among the marly or argillaceous beds; or at the points where the latter pass into the purer calcareous rocks, and which are marked by the intermingling of the limestone and clay strata. The upper members of all the series are generally regarded as having too little argillaceous matter to furnish anything but rich limes.

There is no geological formation to which the terms "hydraulic lime" or "hydraulic cement" can be exclusively applied. No geological formation is capable of providing uniformly either one or the other of these materials from locality to locality. All sedimentary rocks are noted for the distinct variations in their lithological characters. This occurs within very limited areas because of localized causes, which affect the conditions of their deposit. This is especially true of impure limestones with compositions that are suitable for hydraulic mortars, a circumstance due to their geological position. The constituents of these limestones consist of widely-varying proportions of calcium carbonate, magnesium carbonate, silica, alumina, and iron oxide, and generally occur in the beds of passage between deposits that are purely siliceous and/or argillaceous, and those that are purely calcareous or dolomitic. They derive their character from the adjoining underlying and overlying rocks, and approximate one (the underlying or overlying layer) more than the other in proportion to the forces in operation during their formation. For example, if a limestone layer was formed on a sandstone layer, calcareous particles would gradually subside before the deposition of the siliceous matter was complete, and

²³ Ibid., p. 7.

would create a siliceous limestone. Proportions of this limestone would depend upon the manner of deposition, and the nature and extent of the causes by which it was produced and regulated.²⁴

According to Q.A. Gillmore's *Practical Treatise on Limes, Hydraulic Cements, and Mortars*, impure limestone or those possessing hydraulic qualities occur in numerous localities in the United States. The most extensive beds that were reported in his treatise of 1874 were in the valleys of the Appalachian mountains, including the states of New York, New Jersey, Pennsylvania, Virginia, Tennessee, and the northern portions of Georgia and Alabama. They are also found in the northern extremity of this range in Vermont, Massachusetts, and Maine. In addition, they are found to the west of the Appalachian Valley in the western regions of New York, Pennsylvania, Virginia, Tennessee, Kentucky, Ohio, Indiana, and Illinois.²⁵

The observations that have been considered important for the purpose of classification of the limestones and the limes they produce are as follows:

1. quarry and location where limestone extracted
2. number of specimens
3. geological position and mineralogical name
4. geological constitution & importance of beds & country on which observations are made
5. physical characteristics of the stone
6. chemical analysis
7. mode and temperature of burning

²⁴ Q. A. Gillmore, *Practical Treatise on Limes, Hydraulic Cements, and Mortars*. Professional Papers of the Corps of Engineers, U.S.A. No. 9. 5th edition. New York: D. Van Nostrand, 1874, pp. 16-7.

²⁵ *Ibid.*, pp. 15-6.

8. properties of the burnt material
9. method of slaking/hydration of the lime
10. observations on the trials of its hydraulicity
11. general remarks²⁶

Clay-mineral bearing limestones are classified as follows: marly limestones contain 4 - 10% clay minerals; limestone marls contain 10 - 25% clay minerals, and marls which contain 25 - 60% clay minerals. During burning of these limestones hydraulic limes are obtained. Hydraulic limes contain mineral phases which harden hydraulically through absorption of water. Portland-cement clinker is almost exclusively made of these mineral phases. During burning, calcium oxide forms which when in contact with moisture or water forms calcium hydroxide during the slaking of these limes.²⁷

Burning Limestone

In burning limestones, which yield either poor or hydraulic limes, it was believed that early on a chemical action was produced in which the clay, silica, magnesia, iron oxide, and the other components entered into combination with lime. The lime has more affinity for these clay constituents than it has for the carbon dioxide and the calcium and oxygen disassociate. It seeks to quit its original state to enter into a new combination with these components. Therefore, the presence of these ingredients in the limestone, facilitates calcination.²⁸

²⁶ Burnell, *Rudimentary Treatise on Limes*, p. 23.

²⁷ Gunter Strubel et al., "Hydraulic Limes for the Preservation of Ancient Monuments," trans. by W.P. Klemens. Institut für Steinkonservierung (Institute for Rock Conservation) in Hessen, Rheinland-Pfalz und im Saarland e.V. Report No 1 - 1992, p. 1.

²⁸ Burnell, *Rudimentary Treatise on Limes*, pp. 26-7.

It is difficult to achieve firing that produces desirable physical and chemical properties, because the qualities of a lime are seriously affected by the level and rate of heat it is exposed to. Hydraulic limes are not as easy to burn as quicklimes, as they require higher temperatures to calcine than quicklime. In addition, they are easily over-burned, due to the ease with which some of the material fuses.²⁹ Excessive heating causes hydraulic limes to lose their useful properties, but if a lime is under-burnt, they are often poor, and without any hydraulic powers.³⁰ Therefore, there must be a compromise between 'hard burning' and 'soft burning', retaining the beneficial physical characteristics of 'soft burning' (i.e. at low temperature so as to obtain maximum porosity and, therefore, a large surface for reaction of lime with water), while possessing the best possible cementitious properties through 'hard burning' or 'sintering' (maximum hydraulic properties due to formation of cementitious constituents achieved at high kiln temperatures, it is also more efficient burning at higher temperatures). Sintering is to be avoided as far as possible. To achieve the ideal condition during the calcination process, the precise behavior of the clay in the limestone needs to be known.

The impurities of limestone (silica, alumina, ferric oxide, titania, etc.), combine with calcium oxide at the usual firing temperatures of a lime kiln (950 - 1250° C). This occurs at the most active surfaces of calcium oxide or the free lime, consequently, the reactivity of the lime produced is diminished because the impurities render part of the hydraulic lime unavailable for reaction with water and because the portion rendered unavailable would otherwise have been the most reactive.

The reactions between calcium oxide and the clay mineral components are mostly solid state reactions and depend on composition, temperature, and the duration and rate of heating.

²⁹ Searle, *Limestone and Its Products*, p. 475.

The process is greatly influenced by the physical and chemical conditions of specific clay minerals and their distribution in the limestones. Complete combination may not occur, whereas in the manufacturing of Portland cement a complete combination of clay components with calcium oxide is intended and achieved. Unlike manufacturing of Portland cement, formation of cement minerals in hydraulic lime is not entirely governed by the equilibrium conditions and phase relations that occur between calcium oxide, alumina, silica, and iron oxide.³¹

The burning of hydraulic lime is a complex series of reactions. The clay is decomposed at between 400 - 600° C. At 950 - 1400° C it combines in part with some of the lime, forming complex silicates, aluminates, and alumino-silicates, with tricalcium silicate and tricalcium aluminate being the chief ingredients. At around 1200 - 1250° C the carbon dioxide is driven-out from the limestone, which is the top end of the burning temperatures for hydraulic lime. Sintering takes place at 1300 - 1400° C. It should be noted that the higher the Cementation Index is of the hydraulic material, the higher the temperature that must be reached in the kiln, so as to ensure all the silica and alumina being combined with the lime.³² Sintering is the process of turning fine-grained substances into a bulky material through raising temperatures to just below the melting temperature. The burning of cement clinker exceeds temperatures of 1450° C and thus transgresses the sintering limit.³³

Because of the difficulties usually associated with solid state reactions, the desired compounds are not formed in the quantities theoretically expected, especially under the conditions of an industrial process. The result is that the "hydraulic factors", (the silica, alumina,

³⁰ Burnell, *Rudimentary Treatise on Limes*, p. 28.

³¹ Rai, "Hydraulic Lime," p. 376.

³² Searle, *Limestone and Its Products*, p. 476.

³³ Strubel et al., "Hydraulic Limes for the Preservation," p. 1.

and ferric oxide), are left uncombined in the burned product together with corresponding amounts of free lime. In addition, marls used in the burning of hydraulic limes contain much more lime than can possibly be combined with the hydraulic factors even under the most favorable reaction conditions.³⁴

The commercial hydraulic lime that is produced is primarily composed of three materials: 1.) free lime or quicklime; 2.) cementitious material; 3.) material which is more or less inert (such as silica or uncombined calcined clay). The materials vary according to manufacturing conditions.³⁵

Slaking of Hydraulic Lime

The process of slaking hydraulic lime involves the combining of water and the calcined material to hydrate any free-lime (CaO) present in the material. Hydraulic limes require sufficient water to slake the free-lime completely, but as a result, the hydraulic constituents of the lime are likely to lose a part of their hydraulic value in slaking. The rate of slaking depends largely on compactness of the calcined material, the nature of the limestone used, and the impurities present. Limes calcined at temperatures higher than 900° C take longer to slake, ranging between 24 - 48 hours.³⁶

There are three methods of slaking: wet slaking by immersion, hydration by spraying with small quantities of water, and by allowing the lime to air slake (slake spontaneously) by absorbing the moisture from the air. Technically the terms "slaked lime" and "hydrated lime" relate to the same material. The use of the term "hydration" is usually restricted to the process

³⁴ Lea, *Chemistry of Cement*, p. 12.

³⁵ Searle, *Limestone and Its Products*, p. 476.

³⁶ *Ibid.*, pp. 487-8.

which produces a dry, powdered hydrate, where as the term "slaking" is generally used for a process that involves more water and yields a wet hydrate.

Burnell thought when slaking it was important not to mix hydraulic limes with too much water, because this interferes with the crystallization in setting. Because if "imperfectly" slaked, un-slaked particles can be introduced into the mortar, and are likely to expand in slaking and possibly disintegrate the other portions of the mortar. Hydraulic limes absorb considerably less water than a rich lime.³⁷

Wet slaking is the process of mixing hydraulic lime with 3 or 4 times its weight in water, being careful not to add too much water at once, which would drown the lime. The mix should remain at boiling temperature for some time. The mix is stirred with a wooden rake so as to produce a milk or slurry, which is run off into a vessel or a pit. Any pieces of un-slaked lime settle to the bottom and remain when the slurry is transferred. The process ensures complete hydration.

The wet slaking of hydraulic lime proceeds very slowly and may require several days. Moderately hydraulic limes do not begin to slake for 10 - 15 minutes, after which they slake gradually with less activity than an ordinary lime. The normal slaking period for a moderately-hydraulic lime is 2 days while a eminently-hydraulic lime may require 7-14 days. It is necessary to mix the lime well with water, the better they are mixed, the harder the final product.³⁸

Typically the term hydrated lime is applied to the product formed when a lime is mixed slowly with a suitable quantity of water to form dry powder. The water is normally applied in a very fine spray. A chemical combination of calcium oxide (CaO) and water occurs forming

³⁷ Burnell, *Rudimentary Treatise on Limes*, pp. 46-9.

³⁸ Searle, *Limestone and Its Products*, pp. 484-5

calcium hydroxide (CaOH_2). The combination occurs with so much evolution of heat that surplus water is driven off as steam, leaving dry powder as a final product.³⁹

A minimum of 24 hours is currently specified for hydration, presumably because the loss of hydraulic value is negligible, as dicalcium silicate, the most important constituent, is expected to hydrate very slowly. However, other cementitious minerals like tricalcium aluminate, dicalcium aluminosilicate, and tetracalcium aluminoferrite silicate may hydrate very quickly during slaking, resulting in the loss of hydraulic value.⁴⁰

A properly slaked hydraulic lime will usually require only 7 - 8% of its weight in water, 10 - 11% is usually added to allow for loss in evaporation. A good hydraulic lime should fall to powder when immersed in water for 24 hours or when sprayed with suitable quantity of water.

Air or dry slaking is the process of hydrating or slaking the calcined lime by exposing it to the moisture in the air over an extended period of time. Air slaking is not suitable for hydraulic lime because it often yields lime that is not completely hydrated.

Slaking for hydraulic lime is different than for non-hydraulic lime because in addition to free-lime there are cementitious constituents. In hydraulic lime when the free-lime constituent slakes, the result is powder containing unslakeable lumps or clinkers (grappiers). Hydraulic limes do not increase in volume appreciably when slaked and do not produce as much heat as a non-hydraulic quicklime. If only sufficient water is added to lump hydraulic lime, only the calcium hydroxide and magnesia will hydrate. It is important not to add more water than

³⁹ Ibid.

⁴⁰ Rai, "Hydraulic Lime," p. 377.

necessary to slake the quicklime present, unless the hydraulic lime is to be used at once. Excess water will cause some of the cement to harden.⁴¹

After slaking the hydrated lime is passed through a sieve, to sort out any lumps (grappiers). The grappiers or clinkers are sometimes ground and a portion added back to the lime, which adds hydraulicity.⁴²

Artificial Hydraulic Limes

The production of artificial hydraulic limes is discussed as a possible alternative to natural hydraulic limes. It deserves some consideration, because there is the issue of variability of the constituents of hydraulic limestone as a function of natural variability in the beds. The idea of having a consistent product is worth consideration. One artificial lime that Burnell mentions is General Treussart's artificial hydraulic lime; which involved the mixing 5 measures of chalk by volume to 1 of clay, then the paste is burnt. The lime was then slaked with water in which potash and soda were mixed in proportions necessary to bring the solution to 5% acidity.⁴³

Burnell also mentions the research of M. Kuhlmann completed in 1841. From his experiments Kuhlmann was of the opinion that in the cement stones, and potash served as carriers in combination between silica and the lime and gave rise to the formation of silicates when placed in contact with water, it solidified with a hydration similar to that of plaster. He cited as confirmation of his views the fact that if a rich lime were burnt in contact with a dissolution of potash silicate, it would become a hydraulic lime of a superior quality by the

⁴¹ Searle, *Limestone and Its Products*, p. 491.

⁴² Ibid., pp. 492-3.

⁴³ Burnell, *Rudimentary Treatise on Limes*, p. 44.

calcination of a mixture of the rich lime and the alkali silicate in the proportions of from 10 - 12 of the latter, to 100 of the former. Both must be very finely powdered and well mixed or otherwise the reaction would be incomplete, and subsequently solidification would produce a disintegration of the mass.⁴⁴

The artificial hydraulic limes did not attain the same degree of hardness or the same compressive strength as the natural hydraulic limes of the same class. Of the latter, those which were obtained from the closest grained and densest lime stones, were reported to be the most resistant. They were used in preference to the artificial cements. This did not apply (lack of compressive strength) to the over-burnt limes, because Portland cement attained both great tensile and compressive strength.⁴⁵

Searle also discussed the topic of artificial hydraulic lime. He believed that artificial hydraulic lime could be produced by mixing slaked lime and clay in the proper proportions. It also could be made by mixing soft limestone or chalk with clay, grinding them together to form a paste, then molding them into rough bricks and burning them. The proportions of clay and lime or limestone to be used were dependent upon the composition of each, but the addition of one part clay to four parts of rich lime was typical. Also, if argillaceous limestone was enriched with a purer limestone or diluted with clay, the proportions of each could be adjusted so as to produce a lime having the desired properties.

In addition, it was also possible to produce hydraulic lime by under-burning a mixture of limestone and clay or shale, however such a lime may contain a large proportion of wholly inert

⁴⁴ Ibid.

⁴⁵ Ibid., p. 44-5.

material. A mixture of limestone and clay, artificial or manmade, must contain more than 80% calcium carbonate, or the product will contain too much uncombined lime and silica.

Searle concluded that the best hydraulic limes are natural, made from rock containing the ingredients in the right proportions, - an artificial hydraulic lime can not produce as uniform a mixture as nature.⁴⁶

Cementation and Hydraulic Indexes

The property of setting under water is dependent upon the ratio of silica, alumina and iron oxide to lime, assuming the former to all be combined. The Hydraulic Index is a quantitative expression of the hydraulic components (not including iron oxide) and lime, and is found by adding the percentage of silica and alumina and dividing by the percentage of lime. The index oddly omits iron oxide and magnesia, which have an effect on hydraulicity.⁴⁷

The Cementation Index is based on the assumption that silica is present as $3\text{CaO} \cdot \text{SiO}_2$, alumina as $2\text{CaO} \cdot \text{Al}_2\text{O}_3$, and that iron oxide and magnesia replace their equivalents of alumina and lime respectively, forming compounds with similar properties. The Cementation Index is a rough guide that is useful when comparing different limes and forming an opinion on their properties. The Cementation Index is determined as follows:

$$[(2.8 \times \% \text{SiO}_2) + (1.1 \times \% \text{Al}_2\text{O}_3) + (0.7 \times \% \text{Fe}_2\text{O}_3)] / (\% \text{CaO}) + (1.4 \times \% \text{MgO})$$

Common limes have an Index of 0.20, feebly hydraulic limes have an index of 0.20 - 0.60; strongly hydraulic limes have an index of 0.60 - 1.10; natural cements have an index of over 1.10; and Portland cement ideally has an index of 1.00, and actually varies between 1.00 - 1.20.

⁴⁶ Searle, *Limestone and Its Products*, pp. 475-6.

⁴⁷ *Ibid.*, pp. 474-5.

Feebly-hydraulic limes harden only slightly when in contact with water. They include those limes which "set" or become hard after immersion in water for 15 - 20 days and continue to harden for 6 months, after which the increase in hardening is very slow. The change in volume on slaking is very slight. Feebly-hydraulic limes have a Cementation Index of 0.3 - 0.7 and a Hydraulic Index to 0.1 - 0.2.

Moderately-hydraulic limes are those which set after 6-8 days in water and continue to harden fairly rapidly for 6 months, and more slowly for another half year. At the end of this time the mass has the consistency of a soft building stone. The change in volume on slaking is small. Moderately-hydraulic limes have a Cementation Index of 0.5 - 0.9. Based on the limes available at the time of the publication of Searle's text (1935), English hydraulic limes were moderately-hydraulic compared with the limes of Germany and France which were rated eminently-hydraulic. The author suggested that the strength of the English limes can be increased by mixing them with the right proportion of clay.

Eminently-hydraulic limes are those limes that set within 4 days in water, are hard after 1 month, and at the end of 6 months can be worked like stone. The change in bulk on slaking is small. Eminently-hydraulic limes have a Cementation Index of 0.7 - 1.1 and a Hydraulic Index of 0.2 - 0.4. 48

Mortar

Probably the best way to define a mortar is to describe its functions in a building. Mortar serves a number of purposes in a building, as a bedding material, absorbing expansion and contraction and other movements of the building, absorbing compressive loads, wicking water away from the masonry substrate and the building itself, and to some extent bonding the

masonry. Mortar is composed of a binder and an aggregate (generally sand), in such proportions that the volume of binder shall be very slightly in excess of volume of voids in the sand. The quantity of sand will generally vary between 2.5 - 2.75 times that of the cement paste by volume; or 1 part binder to 3 - 3.5 parts of sand by weight. In addition, sometimes additives are added to achieve a desired affect on the mortar, such as pigment for color, pozzolan for set, or an air-entrainer.⁴⁹

The following table contains mortar mixes (by volume) that have been used in practice and are based on hydraulic limes.⁵⁰ Each mix in the table shows a decrease in strength, but an increase in flexibility. For example, strength decreases but flexibility increases from Mix 1 to Mix 2. The mortar mixes are based on practice and should not be taken literally for every circumstance.

⁴⁸ Ibid., pp. 472-3.

⁴⁹ Gillmore, *Practical Treatise on Limes*, p. 208.

⁵⁰ Ashurst, "Technology and Use of Hydraulic Lime," p.130.

Mortar Mixes Based on Hydraulic Lime

| | Mix 1 | Mix 2 | Mix 3 | Mix 4 | Mix 5 | Mix 6 | Mix 7 | Mix 8 | Mix 9 | Mix 10 |
|--|-------|-------|-------|-------|-------|-------|-------|-------|-------|--------|
| Eminently Hydraulic Lime | 1 | 1 | 1 | - | - | - | - | - | - | ½ |
| Moderately Hydraulic Lime | - | - | - | 1 | 1 | 1 | - | - | - | - |
| Feebly Hydraulic Lime | - | - | - | - | - | - | 1 | 1 | 1 | ½ |
| Non-Hydraulic Lime | - | - | - | - | - | - | - | - | - | ½ |
| Brick Powder (reactive) | ½ | - | - | ½ | - | - | ½ | - | - | ½ |
| Well Graded Sharp Sand | 1½ | 2 | 2 | 1½ | 2 | 2 | ½ | 2 | 2 | 1 |
| Soft Sand | - | - | ½ | - | - | ½ | - | - | ½ | ½ |
| Porous Limestone or Brick Aggregate | ½ | 1 | 1½ | ½ | 1 | 1½ | ½ | 1 | 1½ | 1 |
| Mix by Volume | 1:2½ | 1:3 | 1:4 | 1:2½ | 1:3 | 1:4 | 1:2½ | 1:3 | 1:4 | 1:3 |

Selection of aggregate is of great importance. Clean, well graded, sharp sand is the backbone ingredient, while other aggregates have other important, but supportive roles. Soft sand aids in workability and contributes to final color.⁵¹

Ashurst brings up the point that after many years of disuse, it would be surprising if mistakes were not made with hydraulic lime, especially when specification is lacking and experience limited. Unfortunately, it is human nature to blame the materials when problems arise. The author believes that problems will be avoided if the following are observed: read about and understand the available material, provide a full and detailed specification covering materials and work with reference to manufacturer's instructions, select an experienced

contractor (including assistants), submit material samples with manufacture's data sheets, use a lime with a proven record, execute trial work for approval (including mixing and placing procedures), provide slow curing, and close supervision of work.

Hydraulic limes have had an excellent track record in the building industry for the past thirty years. Provided the source stone is well-selected, the burning carefully-controlled and the hydration, mixing placing and curing properly carried-out, hydraulic limes will perform a range of work consistently well.⁵²

Lime Putty Gauged with Hydraulic Lime

Non-hydraulic lime putty can be gauged with hydraulic lime for the purpose of producing a mortar with a set. For the past five years in the U.K. there has been a trend for the use of these mortars.

In a Technical Policy Statement published by English Heritage in 1997, the current growing use of hybrid mortar mixes using a combination of hydraulic lime and non-hydraulic lime has been identified. Concerns were raised because there have been failures, especially with stuccos and renders. There was a moratorium placed on these mixes in any grant-aided English Heritage projects carried-out between June 15, 1997 and June 15, 1998. According to English Heritage, there is no historic precedent for these mixes and little is known about their behavior. English Heritage does not place blame on the use of hybrid mixes alone, but it may be a contributing factor. The moratorium was applied to hybrid mixes and not mixes based solely on non-hydraulic lime hydraulic lime.⁵³

⁵¹ Ibid.

⁵² Ashurst, "Technology and Use of Hydraulic Lime," p. 131.

⁵³ English Heritage, "Hybrid Mortar Mixes," p.1.

Durability of Mortars

Durability can be defined as the ability of a mortar to withstand weathering, chemical attack and any other processes of deterioration. Durability is of prime concern when considering a mortar. Mortar durability can be improved by the means of certain additives and performance requirements. Cement and concrete texts were selected for this section as additional sources of information because of their research and experience on the subject.

Causes of Deterioration

There are various causes of deterioration, including: freeze-thaw action, pollution, and alkali-aggregate reaction which can be aggravated by high temperatures. The combined effects of cold winter and hot summer exposures should be considered when proportioning and mixing of durable mortars; as well as during application and curing. Heat provides activation energy for deterioration processes and water is required for chemical and most physical deterioration processes that take place.

The integrated effects of moisture, heat, and other environmental elements are important and should be contemplated when considering a mortar. The selection and proper installation of appropriate materials is essential in order to achieve mortars that are resistant to deleterious effects of water, aggressive solutions, and extremes of temperature. Sulfates in soil, ground water, or sea water can be resisted by using suitable materials and a properly-proportioned mixture which has been subjected to quality control.

Aggregate is not always an inert filler in mortars. Certain aggregates can react with alkalis in cement, causing expansion and deterioration. Care in the selection of aggregate

sources, and the use of low alkali cement (white cement) and/or pre-tested pozzolans or ground slag will alleviate this problem.⁵⁴

Mortars that are exposed to a combination of moisture and cyclic freezing requires the following:

1. Low water-binder ratio
2. Appropriate air-entrainment
3. Quality materials
4. Adequate curing before first freezing cycle
5. Special attention to construction practices

As the vulnerability of masonry to cyclic freezing is influenced greatly by the degree of saturation, every precaution should be taken to prevent water uptake.⁵⁵

Porosity/Permeability

Porosity can be defined as the total volume of voids of a mortar in relation to the total volume of the mortar. Permeability can be defined as transmission of moisture through the pores, voids, and cracks in mortar joint. Permeable mortars tend to dry out quicker and are less subject to volume change and shrinkage cracking. Harder, denser mortars tend to expand upon wetting and narrow the openings, thereby preventing drying. Water remains trapped in the mortar and dissolves soluble alkali sulfates. The sulfates eventually appear on the face of the masonry and erode it. Leakage tends to occur mainly as a result of shrinkage separation at the mortar-unit interface - a failure of the mortar bond. A high lime mortar (1:2:9) has a porosity of

⁵⁴ American Concrete Institute, *ACI 1996 Manual of Concrete Practice, Materials and General Properties of Concrete, Part I*, (Detroit: American Concrete Institute, 1996), p. 201.2R-2.

⁵⁵ *Ibid.*, p. 201.2R-5.

30 - 35%, about 50% higher than a pure cement mortar. Permeability increases with the increase in lime content.⁵⁶

Water-Binder Ratio

The water-binder ratio (water-cementing materials ratio) is simply the mass of water divided by the mass of binder. The water-binder ratio is important because it is inversely related to compressive strength and is also related to shrinkage. Generally, the higher the water-binder ratio, the weaker the mortar.⁵⁷ The primary factor influencing drying shrinkage is the water content of a mortar mix. Drying shrinkage increases directly with increases in water content.⁵⁸ Frost-resistant concrete should have a water-cement ratio not exceeding the following: thin sections of concrete and those exposed to deicing salts - 0.45; all other structures - 0.50.⁵⁹ These numbers are thought to be applicable for hydraulic lime-based mortars, because the consistency, workability, and compressive strength typically are favorable for hydraulic limes with a water-binder ratio of 0.45 - 0.50.

Of interest, a low water-binder ratio and a period of moist curing is found to decrease permeability as well as segregation and bleeding in cements.⁶⁰

⁵⁶ Robert S. Boynton and Kenneth A. Gutschick, "Durability of Mortar and Masonry," Factors Influencing Mortar Durability Experience with Mortars. Masonry Mortar Technical Notes #1, (Arlington: National Lime Association, 1964), p. 4.

⁵⁷ Steven H. Kosmatka et al., *Design and Control of Concrete Mixtures*, Fifth Ed., (Ottawa: Canadian Portland Cement Association, 1991), pp. 80-1.

⁵⁸ Ibid., p. 10.

⁵⁹ American Concrete Institute, *ACI 1996 Manual of Concrete Practice*, p. 201.2R-6.

⁶⁰ Kosmatka, *Design and Control of Concrete*, p. 8.

Air-Entrainment

Air-entrained mortar is produced through the use of an air-entraining admixture added at the mortar mixer, or factory air-entrained hydrated lime or hydraulic lime. The resulting air content depends on many factors, including the properties of the materials being used (lime, chemical admixtures, aggregates, pozzolans, etc.), mixture proportions, type of mixer, mixing time, and temperature. The preferred procedure is to use an air-entrained admixture, because the amount of air-entrainment can be varied to give the desired air content. This method is however problematic on site, as quality-control can be difficult. Pre-entrained limes and hydraulic limes are more convenient to use, but one loses the possibility of any site variance in the level of entrainment.

It has been proven that additions of small amounts of entrained air to mortar improve plasticity, weatherability, and durability, - the amount is probably in the range of 5 - 10%. Above this, the air-entrainment is thought to adversely affect the masonry bond. Some authorities favor a maximum of only 5 - 6% where as Boynton favors the range of 5 - 10%. Lower air content is thought to improve durability but yet not sacrifice bond strength. Too little entrained air will not protect cement paste against freezing and thawing stresses. Too much air will lower the strength.⁶¹

Air-entrained masonry which is properly proportioned with quality materials, manufactured, placed, finished, and cured can resist cyclic-freezing for many years. Without entrained-air, the paste matrix surrounding the aggregate particles may fail when it becomes critically saturated and is frozen. However, if the matrix contains an appropriate distribution of

⁶¹ Boynton, "Durability of Mortar and Masonry," pp. 3-4.

entrained air voids, characterized by a spacing factor less than 0.008 in. (0.20 mm), freezing does not produce destructive stress.

Air-entrained mortar should be able to withstand the effects of freezing as soon as it attains a compressive strength of about 500 psi (3.45 MPa) provided there is no external source of moisture. This is approximately 3 days for the Jura (not air-entrained) and Riverton, and probably twenty-eight days for the Unilit.⁶²

Air contents are given for two conditions of exposure; severe and moderate. Severe exposure is defined as outdoor exposure in a cold climate where there may be almost continuous contact with moisture prior to freezing. Moderate exposure is defined as outdoor exposure in a cold climate where there will be only occasional exposure to moisture prior to freezing. An example is a typical exterior wall. The American Concrete Institute recommends about 9% of air in the mortar for severe exposure, and about 7% for moderate exposure. The Concrete Institute further recommends percentages of air based on aggregate size; for example for masonry with a nominal maximum aggregate size of 9.5 mm, the average air content percentage is 7.5% for severe exposure and 6% for moderate exposure. As the nominal maximum aggregate size increases, the average air content percent decreases.⁶³

Aggregate

Aggregate gives mortar its characteristic color, texture, and cohesiveness. The grains should be sharp, and angular. This type of aggregate interlocks and forms a type of mesh in the mortar. Other functions of aggregate include: reducing shrinkage during drying; contributing to

⁶² American Concrete Institute, *ACI 1996 Manual of Concrete Practice*, p. 201.2R-7.

⁶³ American Concrete Institute, *ACI 1996 Manual of Concrete Practice*, p. 201.2R-6.

compressive strength; possibly acting as air-entrainers; preventing cracking; increasing porosity; and reducing the cost of mortar by acting as a filler.

The gradation of the aggregate should have the highest proportion of material in the middle range of sizes with decreasing proportions at either end of the size spectrum.⁶⁴ This corresponds with the gradation of ASTM C 144, Standard Specification for Aggregate for Masonry Mortar.

The quantities of sand used vary according to the nature of the limes, and also of the sand itself. The greater percentage of sand the rich limes are able to contain in a mortar, may perhaps account for the partiality of the builders in their favor in the past.⁶⁵

Working of Hydraulic Lime Mortars

The best hydraulic limes lose much of their qualities if exposed to the air for too long a period of time; it is recommended to work them only for the time necessary to ensure perfect reduction to the state of hydrates and the thorough mixing of the lime and sand.⁶⁶ Manufacturer's recommendations for the use of a hydraulic lime mortar typically recommend use within two hours of being mixed. With hydraulic lime mortar it is said to be bad to "work up" a mortar again which has been sitting for some time, because "once the setting process of the mortar is interrupted, it is often put to stop forever".⁶⁷

⁶⁴ Historic Scotland, "Preparation and Use of Lime Mortars," *Historic Scotland Technical Advice Note 1*, (Edinburgh, Scotland: Historic Scotland, 1995), p. 14.

⁶⁵ Burnell, *Rudimentary Treatise on Limes*, pp. 68-9.

⁶⁶ *Ibid.*, p. 69.

⁶⁷ *Ibid.*, p. 49.

Curing and Carbonation

Hydraulic lime under goes both a hydraulic hardening (as a cement) and carbonation process (as a lime) when curing.

The hydraulic hardening of hydraulic lime has already been discussed in the section "Constituents". The formation of colloidal compounds by lime, silica and water are the most important factors in hydraulic hardening. The formation of colloidal hydrated compounds of calcium oxide and alumina, the calcium aluminate hydrates, plays a less significant role. The hydration of dicalcium silicate proceeds very slowly and requires a long curing time, (weeks or months) but leads to high strengths. The significant presence of free-lime in hydraulic lime was also discussed in the constituents section. Free-lime hardens through carbonation.

The freedom of the water from carbon dioxide-in-solution is also a necessary condition for the successful use of hydraulic limes. Their success partially depends upon the slow, gradual manner in which the free-lime absorbs the carbon dioxide from the atmosphere, and crystallizes about the nuclei offered to their action.⁶⁸ The free lime resumes the crystalline form of the carbonate of lime, by arranging themselves around the bodies with which they are in contact. Carbonation goes on from the outside to the inside, with a speed depending on the nature of the lime and also that of the sand. Surprisingly, (according to Burnell) the chemical nature of the sand has nearly as much influence upon the progress of the crystallization as its mechanical structure. It was found that the carbonization of the lime never attains the same degree as that which exists in the limestone.⁶⁹

⁶⁸ Burnell, *Rudimentary Treatise on Limes*, p. 70.

⁶⁹ *Ibid.*, p. 51.

The depth to which carbonation penetrates into lime mortar in a given time, and, to a certain extent, the hardening from that varies inversely with the hydraulic properties of the lime, which depend upon its constituents.⁷⁰ Hydraulic lime undergoes complex chemical change when in contact with water and sets to a hard mass, it does this equally well in air (if damp cured) or under water. If the supply of water is insufficient the hardening will be incomplete.⁷¹

The thickness of the carbonated film for the hydraulic limes is, at the end of the first year, about 1/4"; about 1/8" for the rich limes. The further the process continues into the mortar, the annual progress decreases proportionally. With increasing film thickness, there is an increasing resistance for the absorption of the gases necessary to produce carbonation.⁷²

Compressive Strength

Mortar was originally conceived of as a means of bedding masonry units and bonding them together, i.e. mortar serves in the capacity of a gasket or washer and resilience is necessary to cushion deflection. It binds masonry units together into a giant mass which must often support heavy loads, must possess adequate strength with a generous safety factor. Mortar strength, however, is often over-emphasized to the detriment of other essential properties. Some of the factors effecting strength are discussed below.⁷³

Strengths of mortars can be altered by as much as 25 - 200% by the following factors: slight changes in sand gradation; consistency of mix or percent of initial flow; slight variation in mix proportions; modification in curing conditions; type of lime (whether high calcium or

⁷⁰ Gillmore, *Practical Treatise on Limes*, p. 187.

⁷¹ Searle, *Limestone and Its Products*, p. 571.

⁷² Burnell, *Rudimentary Treatise on Limes*, p. 52.

⁷³ Robert S. Boynton and Kenneth A. Gutschick, "Strength Considerations of Mortar," *Masonry Mortar Technical Notes #2*, (Arlington, V.A.: National Lime Association, 1964), p. 5.

dolomitic); hydrate or putty from quicklime; slight changes in atmospheric conditions such as temperature and humidity during curing; and the skill and experience of laboratory technician.⁷⁴

Measured by standard consistency or flow, the water-binder ratio steadily increases with increasing proportions of lime. In general, decreases in either water retention or sand-carrying capacity parallel an increase in strength for all mortars. The 28 day strength of mortars, regardless of lime content, average about 60% higher than 7 day strength.

Another factor affecting strength is air-entrainment. Air-entrainment lowers the strength of all mortar types. With modest amounts of air the strength losses are slight, but with percentages of entrained air over 15%, losses are significant as the air content rises.

Tensile Strength

The tensile strength of all proportions of lime-cement mortars, as well as straight Portland cement and non-hydraulic lime mortars usually can be estimated from known compressive strengths. Tensile strength would be about 12% of the compressive strength, with a range of 7 - 20%.⁷⁵

Regardless of mortar composition, both tensile and compressive strength values increase as the water-binder ratios are decreased. Generally, workability in mortar decreases as compressive strength increases in the absence of entrained air, and vice versa.

Hydraulic Lime Standards

Currently there are four known standards for hydraulic lime; The German Industrial Standard (Deutsche Industrie Norm) DIN 1060, American Society for Testing and Materials C

⁷⁴ Ibid., p. 2.

⁷⁵ Ibid., p. 6.

141, and the European Pre Standard ENV 459. The hydraulic lime standard generally referenced for this paper was ASTM C 141 Standard Specification for Hydraulic Hydrated Lime for Structural Purposes.

ASTM defines hydraulic hydrated lime as:

The hydrated dry cementitious product obtained by calcining a limestone containing silica and alumina, or a synthetic mixture of similar composition, to a temperature short of incipient fusion so as to form sufficient free lime (CaO) to permit hydration and at the same time leaving unhydrated sufficient calcium silicates to give the dry powder, meeting the requirements herein prescribed, its hydraulic properties.⁷⁶

The definition divides hydraulic limes into two types:

- 1.) High calcium hydraulic hydrated lime - a lime that contains not more than 5% magnesium oxide (of the nonvolatile portion).
- 2.) Magnesium hydraulic hydrated lime - a lime containing more than 5% magnesium oxide (of the nonvolatile portion).

The chemical composition of hydraulic hydrated lime, calculated to the nonvolatile basis, is contained in the below chart.⁷⁷

Chemical Composition of Hydraulic Hydrated Lime (ASTM C 141)

| | Min % | Max % |
|--|-------|-------|
| Calcium and magnesium oxides (CaO and MgO calculated to the nonvolatile basis) | 65 | 75 |
| Silica (SiO ₂ calculated to the nonvolatile basis) | 16 | 26 |
| Iron and aluminum oxides (Fe ₂ O ₃ and Al ₂ O ₃ calculated to the nonvolatile basis) | | 12 |
| Carbon dioxide (CO ₂ on an as received basis) | | 8 |

⁷⁶ American Society for Testing of Materials, "C 141-85 (Reapproved 1994) Standard Specification for Hydraulic Hydrated Lime for Structural Purposes," *Annual Book of ASTM Standards*, Vol. 04.02, Cement; Lime; Gypsum, (West Conshohocken, P.A.: ASTM, 1996), p. 127.

⁷⁷ Ibid.

The C 141 standard is insufficient in that it does not divide hydraulic lime into feebly, moderately, or eminently-hydraulic nor does it attempt to define an artificial hydraulic lime.

The German Industrial Standard (Deutsche Industrie Norm) DIN 1060 defines air-lime, white-lime, dolomitic-lime, hydraulic-lime and high-hydraulic lime. Artificial-hydraulic limes are included in the "high-hydraulic limes". High-hydraulic limes are manufactured in a process of burning limestones marls, whereas artificial high-hydraulics are produced through the mixing of several manufactured binding agents. According to the standard, there are no requirements for chemical composition for high-hydraulic limes, only physical prerequisites. They may contain additives to improve their properties.

There is also a European Pre-standard ENV 459-1; 1995. Hydraulic limes being produced from argillaceous limes are designated "natural hydraulic limes" (NHL). Limes modified by the addition of pozzolanic or hydraulic materials, up to 20% by mass are designated NHL-P. This new revised draft form of the standard is currently under review.⁷⁸

Currently there is no British Standard for hydraulic limes, but apparently in the near future, a new version of BS EN 459-1 (Building Lime Part 1) will be expanded to include hydraulic limes.⁷⁹

Testing

In addition to the research of the literature on hydraulic limes, a testing phase was completed. This was designed to test the properties and performance of hydraulic limes that

⁷⁸ Strubel et al., "Hydraulic Limes for the Preservation," p. 1.

⁷⁹ Ashurst, "Technology and Use of Hydraulic Lime," p.131.

were available in North America. Three commercially available hydraulic limes were selected for testing, one lime from United States and two from Europe. The reason for the selection of these particular limes was because they were the only known hydraulic limes currently being distributed in North America.

Limes

The three hydraulic limes were Jura-Cement-Fabriken, Riverton Hydraulic Lime, and Unilit Hydraulic Lime. None of the limes used for this project were over six months old.

Jura-Cement-Fabriken

The Jura hydraulic lime is from the Jura Cement Fabriken Wildeg in Switzerland, which has one of the last vertical shaft kilns producing hydraulic lime.⁸⁰ The color of the lime is a light brown to buff. The raw material is obtained from the mining of a marl quarry of the Jurassic Malm formation. The marl is broken down to a size of approximately 30 mm and mixed with 4 - 7% coke (petrol or anthracite). The mixture is placed in the vertical shaft kilns from the top and the burnt clinker is removed from the bottom. The mixture is burned at a temperature of about 900-1000° C, about 500° lower than cement clinker. The resulting warm hydraulic lime clinker is passed under a water spray to reduce the free lime content. The manufacturer states that 50 liters of water is needed per metric ton. The clinker is then stored for at least one month. The manufacturer adds 4 - 5% natural gypsum (magnesium sulfate) is added to the clinker to control setting time. The mix is then ground in a ball mill to a finess of 7500 m²/g.⁸¹ The

⁸⁰ Distributed in Canada by Specialty Construction Products Ltd., 77 Paquin Rd. Winnipeg, Manitoba, Canada. R2J 3V9, 1-(204) 661-9157.

⁸¹ Jura-Cement-Fabriken, "Hydraulic Lime - A Structural Lime with a Long History," Jura-Cement-Fabriken Product Literature, Wildeg, Switzerland, June 1996.

chemical composition was unavailable for Jura, but based on its compressive strength (1854 psi or 12.8 MPa at 28 days) is considered an eminently-hydraulic lime.⁸²

Riverton Hydraulic Lime

The Riverton Corporation is located in Front Royal, Virginia.⁸³ Riverton is currently the only known producer of hydraulic lime in North America. The color of the lime is a light gray/buff. Air-entrainment is added to the lime by the manufacturer, somewhere in the range of 8-10%. Riverton did not aggressively market their hydraulic lime, as it was mostly used as an additive for their custom mortar mixes, but this is changing. The chemical composition as provided by the manufacturer⁸⁴ is as follows:

Riverton Typical Chemical Analysis

(ignited basis) % wt

| | |
|--------------------------------|-------|
| SiO ₂ | 16.09 |
| Al ₂ O ₃ | 4.80 |
| Fe ₂ O ₃ | 1.15 |
| CaO | 69.89 |
| MgO | 4.31 |
| SO ₃ | 1.60 |
| Na ₂ O | 0.25 |
| K ₂ O | 1.12 |

⁸² Robert S. Boynton, *The Chemistry and Technology of Lime and Limestone*, p. 453.

⁸³ Distributed in Canada by Liner Rolpanit Inc. North America, 430 Montrose Ave., Toronto, ON, Canada, M6G 3H1, 1-(416) 534-1511.

⁸⁴ Riverton Corporation, "Hydraulic Lime," Riverton Product Literature, (Front Royal, V.A.: Riverton Corporation, undated).

Based on the active clay constituents present (approximately 22%) and its compressive strength (1,127 psi or 7.78 MPa at 28 days), the Riverton is considered an eminently-hydraulic lime. The firing temperature of the lime was not available.

Unilit B-Fluid X

Unilit is quarried in northern Italy and manufactured in Belgium.⁸⁵ Unilit B-Fluid X is an organic binder based on natural hydraulic lime. The color of the lime is buff. It is characterized by a low soluble-salts content. The manufacturer adds pozzonlana (trass) to adjust the degree of hydraulicity, to compensate for any fluctuations in the quarry; producing a standard performance. They recommend mixing from 5 - 8 minutes. The mortars are workable for 2 hours. Their drying period is 24 - 48 hours, and they have to be protected from frost for 48 - 72 hours after their application. The firing temperature is not known. The maximum storage time as recommended by the manufacturer is six months. The lime is packaged in 30 kg bags.

Unilit states that the B-Fluid X will store large quantities of salts which may come from the substrate. This is due to its porosity and its own low soluble salts content. The B-Fluid X salt content is as follows: Ca++ 1.29%, K+ 0.41, Na+ 0.07.⁸⁶

The chemical composition was unavailable for Unilit, but based on its compressive strength (596 psi or 4.11 MPa at 28 days) is considered a moderately-hydraulic lime.⁸⁷

⁸⁵ Distributed in Canada by Liner Rolpanit Inc. North America, 430 Montrose Ave., Toronto, ON, Canada, M6G 3H1, 1-(416) 534-1511.

⁸⁶ Swolfs International Trade, "Unilit B Fluid X," Product Literature, (Anterpen, Belgium, undated).

⁸⁷ Robert S. Boynton, *The Chemistry and Technology of Lime and Limestone*, p. 453.

Fineness

The fineness of a cementitious material affects the rate of hydration and the heat release of that material. The greater the fineness of a material increases the rate at which at mortar hydrates, which accelerates the strength development. This property is manifested principally in the first 7 days of curing.⁸⁸ Therefore fineness may play a role in the early durability of a mortar.

The fineness of the limes was determined according to ASTM C 141. The standard requires that a 100 g sample should not leave more than a 0.5% residue on a No. 30 (600- μ m) sieve and not more than 10% on a No. 200 (75- μ m) sieve. A 100 g hydraulic hydrated lime sample is placed on the No. 30 sieve nested above the No. 200 sieve. The lime is washed through the sieves by means of a stream of water from a rubber tubing attached to a faucet. The end of the tubing was pinched to increase pressure and facilitate the process. The rinsing process was continued until clear water flowed from the sieves or 15 minutes of rinsing had expired. The sieves were then dried and weighed to determine the amount of residue that remained in the sieves. The following table lists the limes and the corresponding residues left for each sieve.⁸⁹

Fineness of Hydraulic Hydrated Limes (ASTM C 141)

| Lime | % residue remaining on No. 30 (600- μ m) Sieve | % residue remaining on No. 200 (75- μ m) sieve |
|----------|--|--|
| ASTM | 0.5 | 10.0 |
| Jura | 0.0 | 11.9 |
| Riverton | 0.0 | 10.7 |
| Unilit | 1.6 | 10.0 |

⁸⁸ Kosmatka, *Design and Control of Concrete*, p. 21.

⁸⁹ ASTM C 141 -85, pp. 127-8.

The limes were all fairly close to the ASTM specification, with 1.9% higher being the greatest difference. The Unilit was the only lime that was higher than the specification for the No. 30 sieve by being 1.1% higher. The Jura and the Riverton easily met the specification not having any residue remaining on the No. 30 sieve, but they were both over the specification for the residue remaining for the No. 200 sieve; the Jura having 1.9% and the Riverton having 0.7% more than the specification.

Aggregate

The type of aggregate used for the testing procedures closely adhered to ASTM's C 144 Standard Specification for Aggregate for Masonry Mortar. The specification calls for an aggregate which is either a natural or manufactured sand. A natural sand was used from a local construction distribution center, Dominion Coal Building Supplies, Toronto.

The specification calls for the aggregate to be graded within the below limits for natural sand.

ASTM C 144 - Percent Aggregate Passing

| Sieve Size | Natural Sand | Dominion Coal Concrete Sand |
|-----------------------|--------------|-----------------------------|
| No. 4 (4.75 mm) | 100% | 100% |
| No. 8 (2.36 mm) | 95 - 100% | 88.2% |
| No. 16 (1.18 mm) | 70 - 100% | 76.3% |
| No. 30 (600 μ m) | 40 - 75% | 58.7% |
| No. 50 (300 μ m) | 10 - 35% | 27.2% |
| No. 100 (150 μ m) | 2 - 15% | 5.1% |
| No. 200 (75 μ m) | 0 - 5% | 0.6% |

The specification requires that not more than 50% of the sand should not be retained between any 2 consecutive sieves and that not more than 25% be retained between No. 50 and the No. 100 sieve.⁹⁰ The aggregate meets these criteria.

The sand was selected because of the similarity of the gradation to the ASTM standard, its availability, its consistency, and its wide use by local masonry contractors. It was used in the dry condition to avoid an additional variable of water content. The sand was air dried by spreading it out over a sheet of polyethylene in the laboratory.

Bulking of Sand

Dry sand increases in bulk volume when water is added. The sand was measured for volume increase when in a damp condition compared to a dry condition. This circumstance is important because there can be a great disparity in quantities of sand used between damp and dry sand. If sand is added dry to a mortar mix, more sand is added than if the same volume of damp sand was used. This may result in too much sand being used and disparity in the binder : aggregate ratio.⁹¹ It was determined that the aggregate increased by 33% from a dry condition to a damp, loose condition.

The volume change was measured by taking a known volume of aggregate in a plastic graduated beaker (300 ml) and lightly misting it. With the aid of another beaker, the sand was transferred back and forth between the containers as with a cocktail mixer. Additional water was added as necessary and the shaking continued until the sand was damp and loose, not clumpy.

⁹⁰ American Society for Testing and Materials, "C 144, Standard Specification for Aggregate for Masonry Mortar," *Annual Book of ASTM Standards*, Vol. 4.02, Concrete and Aggregates, (West Conshohocken, P.A.: ASTM, 1996), p. 91.

⁹¹ Morgan Phillips, "A Source of Confusion about Mortar Formulas," *APT Bulletin, The Journal of Preservation Technology*, Volume XXV Numbers 3-4, 1994, pp. 51-2.

The damp sand was lightly agitated until the surface was flat and the volume again measured. The sand increased in volume to 400 ml; an increase of 33%.

Aggregate Void Ratio

The sand's void ratio was determined in an attempt to measure the voids in the aggregate mass. When lime is mixed into a paste, it fills the voids of the aggregate it is mixed with, accompanied with the effect of decrease of volume, according to Burnell three-fourths of their collective volumes.⁹² Dry aggregate was filled to the top of a 500 ml container and leveled off with a straight edge. A beaker full of water was weighed and recorded. The water was poured into the container of sand until visible at the top of the sand. The water was again weighed to determine the amount of water used to fill the voids. The process was repeated to ensure accuracy. The void ratio of the aggregate was determined to be approximately 30%, which is with in reason. Therefore, it would require 30% binder or a ratio of approximately 1 : 3 binder to aggregate to fill the voids in the dry or saturated aggregate.⁹³

Mixing

Procedure

The procedure for mixing as well as much of the testing methods followed ASTM's C 780 - 96, Section A11, Standard Test Method for Preconstruction and Construction Evaluation of Mortars for Plain and Reinforced Unit Masonry. ASTM 780 was selected because it furnishes numerous tests for measuring the performance of mortars. It is probably the most comprehensive standard designed for preconstruction and construction evaluation of mortars.

⁹² Burnell, *Rudimentary Treatise on Limes*, p. 70.

⁹³ Historic Scotland, "Preparation and Use of Lime Mortars," *Historic Scotland Technical Advice Note 1*, (Edinburgh, Scotland: Historic Scotland, 1995), p. 16.

The standard provides a procedure for sampling and testing mortars for composition and plastic and hardened properties, either before or during construction. The procedures in the standard are considered applicable for evaluating mortars common in use for plain and reinforced unit masonry. The standard states that "it does not attempt to claim or substantiate specific correlations between the measured properties and mortar performance in the masonry, but that it can be used along with other information to formulate judgments about the performance of the masonry."⁹⁴

The procedure calls for preparing and mixing the mortar in the laboratory using the materials and proportions intended for construction and using a mixer that is similar to that intended for use in construction. The standard also requires that the masonry sand be in the damp, as-received condition. This was deviated from in that dry sand was used instead, so that the exact quantity of water used could be determined and for repeatability of procedures. The mixer was electrically driven Milwaukee 1/2 inch drill (catalog number 1610-1) which is typically used on construction sites for the mixing of specialty mortars. The drill was powered by a 7.0 amp, 120 volts 60 Hz motor which produced 650 rpm. The mixing bowl was stainless steel and had a nominal capacity of at least 5.0 liters.

The hydraulic hydrated limes were sieved in dry, powder form with a No. 16 (1.18 mm) laboratory test sieve prior to use. This procedure thoroughly mixed the sample, broke up lumps, and removed any foreign materials. A standard mortar mixture was used in a ratio of 1 : 3 binder (lime) to aggregate (sand) by weight.⁹⁵

⁹⁴ American Society for Testing and Materials, "C 780 Standard Test Method for Preconstruction and Construction Evaluation of Mortars for Plain and Reinforced Unit Masonry," *Annual Book of ASTM Standards*, Vol. 4.05, Chemical Resistant Materials; Vitrified Clay, Concrete, Fiber-Cement Products; Mortars; Masonry, (West Conshohocken, P.A.: ASTM, 1996), p. 435.

⁹⁵ *Ibid.*, p. 128.

The standard also calls for pre-batching the mortar materials, by weight, to meet the volume proportions. Volume proportions were not considered. The constituents (hydraulic hydrated lime and aggregate) were measured by weight and pre-batched placing the constituents in labeled plastic bags. The water was also measured by weight with the intent of being more precise. The pre-batching allowed for exact and easy mixing. The same quantities were used for each hydraulic lime mix: 712.5 g water or 47.5% of the binder, 1500.0 g of hydraulic hydrated lime, and 4500.0 g of aggregate; or for smaller mixes 750 g of binder to 2250 g of aggregate to 356.25 g of water. This weight ratio of binder to aggregate translates to a ratio of approximately 1 : 2 to 2.5 by volume binder to aggregate.

The binder to aggregate ratio of 1 : 3 by weight was selected for the mortars for the following reasons: C 141 (Hydraulic Hydrated Lime for Structural Purposes) specifies using a 1 : 3 mix by weight for testing of compressive strength; using a balance is exact, reproducible and more precise than volume measurements; pre-batching of constituents was possible; the 1 : 3 ratio by weight is also used by a German study on hydraulic lime for preservation and was found in other documents.⁹⁶

ASTM C 780 called for the mortar to be mixed in the following sequence:

1. water - approximately 1/2 the estimated amount required
2. sand
3. cementitious material, and
4. balance of the mixing water required to produce the desired consistency.

⁹⁶ Strubel et al., "Hydraulic Limes for the Preservation," p. 22.

The standard also calls for the mixing of the mortar at normal speed for a total of 5 minutes after completion of the first charging sequence.

The mixing procedure was deviated from the standard as follows: The full amount of water was added to the bowl. The hydraulic hydrated lime was added to the water and mixed for one minute. The entire quantity of sand was added slowly over 1 minute. The mortar was then mixed for 5 minutes. The standard was deviated from because the manufacturers suggest that the hydraulic lime be added to the water. This method provides a more thorough mortar mix and avoids clumping of the lime. According to Burnell, it is a universal rule that all limes should be reduced to a paste before being mixed with other ingredients.

A majority of the testing took place over the summer of 1997. Typical laboratory conditions during this period ranged from a humidity of 30 - 40% and a temperature range of 72 - 76° F. Following mixing, the consistency was determined for every mix as described below.

Plastic Mortar Properties

Freshly mixed mortar should be “plastic” or pliable and generally capable of being molded or shaped with the hands like a lump of modeling clay.⁹⁷ The testing of plastic mortar properties is the testing of freshly mixed mortar. The testing of these properties helps determine whether or not alterations should be made to a mix.

Consistency by Cone Penetration (Test Method ASTM C 780 A1)

Consistency determination by cone penetration aids in the determination of the plasticity of the mortar. Cone penetration also allows for the gauging of water additions for mortars being

⁹⁷ Kosmatka, *Design and Control of Concrete*, p. 2.

considered in preconstruction tests. The test also helps determine the relationship between the water content and the consistency. This is determined by the depth of penetration of a conical plunger into a mortar sample that is held in a 400 ml brass cylinder having a inside diameter of 3" (76 mm) and a depth of approximately 3 1/2" (88 mm).⁹⁸

The consistency of the mortar was determined immediately after mixing each batch of mortar. The desired consistency range (based on preparing preliminary mortars and previous testing experience) was between 15 - 30 mm. The consistency of all mortar mixes tested fell between 17 - 28 mm, with Riverton having the greatest and Jura having the least penetration. The Riverton is assumed to have the highest consistency because it has air entrainment added, which is known to increase plasticity.

Time Of Setting

The time of setting was not determined because the 24 hour compressive strength was determined for each hydraulic lime. All mortars had an initial set within 24 hours.

Mortar Air Content (Test Method ASTM C 780 A5)

Mortar air content is a method of determining the air content of freshly mixed mortar, and evaluating mortars which contain air-entrainers. The air content of the mortars was determined using the pressure meter method according to ASTM C 780 A6, Mortar Air Content Test Method.⁹⁹ The mortar was placed in the pressure meter measuring bowl in 3 equal layers. Each layer was tamped 25 times to consolidate the layers and the sides of the bowl were tapped with a mallet 10 - 15 times to level the surface and remove any large air bubbles. The excess mortar was removed and the cover clamped in place. Pressure was added by means of the hand

⁹⁸ ASTM, "C 780", p. 439.

pump. The pressure was released and the air content determined and recorded. The air-entrainment percentages are recorded in the table below.

Air Content of Hydraulic Lime Mortars

| Lime | Air Content |
|------------------|--------------------|
| Jura | 4.5% |
| Riverton | 6.0% |
| Unilit B-Fluid X | 3.8% |

Riverton had the highest air content at 6%. This is to be expected because Riverton has air-entrainment added, but it was lower than anticipated, because the company claims to add air in the range of 8 - 10%. Riverton meets the requirement for air-content for a durable mortar. The Jura and the Unilit fall in the range for air-content of a typical mortar with no air-entrainment added, but are too low to be considered durable.

Hardened Mortar Properties

Compressive Strength

The compressive strength of the mortars was determined based on ASTM standard specifications C 141 Hydraulic Lime for Structural Purposes and C 780 A7 Compressive Strength of Molded Masonry Mortar Cylinders and Cubes. The compressive strength of the mortars was tested at 24 hours, 3 days, 7 days, and 28 days.

The mortars were mixed in a 1 : 3 ratio by weight as specified by ASTM C 141. The test specimens were 2" cubes (50.8 mm). A minimum of 3 specimens were made for each testing

⁹⁹ Ibid. p. 444.

period. The molds were brass gang molds with 3 cube compartments and were compliant with the standard.

The interior surfaces of the molds were covered with a thin film of mineral oil to act as a release agent for the specimens. The coating of the molds was carried out before the mixing of the mortar. Immediately after taking the consistency reading, the molds were filled half way with mortar and were tamped a total of 32 times with a maple rod. The tamping helped ensure uniform filling of the mold. The mold was then filled the rest of the way and tamped 32 times. The excess mortar was cut away to leave the mortar's plane surface flush with the top of the mold by drawing the edge of a trowel across the top of the mold.

Immediately after casting the specimens, the molds were covered with damp burlap and were wrapped entirely in plastic wrap. The molds were placed in an insulated damp cooler. These precautions were taken to maintain a constant humidity and temperature.

Determination of Compressive Strength

The "24" hour specimens were removed from the cooler after 24 hours. They were de-molded and immediately tested. The remaining specimens were left in the chamber to damp cure for a total of 3 days. After 3 days all the remaining specimens were removed from the chamber and were de-molded. The "3 day" specimens were tested and their compressive strength determined. The remaining specimens were allowed to air dry until they were 7 days old, exposing all sides. The "7 day" specimens were tested and their compressive strength determined.

At the age of 7 days the "28 day" specimens were placed in water and remained there until it was time for testing. All sides of the specimens were exposed to the water. After 21 days

of being submersed, the specimens were removed from the water and surface dried with a damp cloth and tested.

The specimens were placed in the testing machine below the center of the upper bearing block. The load was applied to surfaces of the cube that were in contact with the truly plane surfaces of the mold. The rate of the load application was adjusted so that the entire load was applied without interruption at a rate where the maximum load was reached in between 20 and 80 seconds from the start of loading. The total maximum load, as indicated by the testing machine, was recorded and the compressive strength was determined in pounds per square inch and MPa. The average compressive strength of all acceptable test specimens made from the same sample and tested at the same time period was determined to the nearest pound per square inch and MPa. Specimens that were faulty or that gave strengths differing by more than 15% from the average value of all test specimens made from the same sample and tested during the same time period were discarded. The compressive strength data can be found in Appendix A1-A2.

ASTM C 141 calls for an average compressive strength at 7 days to be not less than 250 psi (1.7 MPa) at the age of 7 days. All three limes exceeded this criteria from least to greatest as follows: 1.) Unilit 429 psi or 2.96 MPa 2.) Riverton 908 psi or 6.27 MPa 3.) Jura 1237 psi or 8.53 MPa.

In addition, the standard calls for an average compressive strength at 28 days to be not less than 500 psi (3.4 MPa) at the age of 28 days.¹⁰⁰ All 3 limes exceeded this criteria from least to greatest as follows: 1.) Unilit 596 psi or 4.11 MPa. 2.) Riverton 1127 psi or 7.78 MPa. 3.) Jura 1854 psi or 12.80 MPa. For comparison, the average strength for 1 : 2 : 9 mix (cement :

¹⁰⁰ ASTM, "C 141," pp. 127-8.

lime : sand), ASTM Mortar Designation O, is 900 psi. with a range of 750-1200 psi. A Portland cement / sand mortar in a ratio of 1 : 2-3 has an average strength of 4,200 psi with a range of 3,800-4,600 psi.¹⁰¹

The compressive strength of the Jura and Riverton were measured at 200 days. A surprising increase of strength occurred since the taking of the 28 day measurements. The compressive strength for Riverton increased by more than 250% and for Jura close to 200%. The samples were damp-cured for 3 days in their molds and water-cured for 21 days as the above samples for 28 day strength. The average 200 day compressive strength for the Jura water-cured samples was 3,603 psi/ 24.9 MPa. The 200 day compressive strength for the Riverton water-cured samples was 2,837 psi/ 19.6 MPa.

In addition to the wet-cured samples, air-cured samples of the Jura and Riverton were cast and were tested for compressive strength. The reasoning behind this was to see what affect water curing had on the strength of the mortars. The samples were damp-cured in their molds for 3 days and air-cured for the duration of their existence until crushed at 200 days. The compressive strength for the air-cured Riverton was 2,224 psi/ 15.4 MPa, an approximately 200% increase in strength from the 28 day strength. The compressive strength for the Jura air-cured mortar 1,988 psi/ 13.7 MPa, or only a 7% increase from the 28 day strength. In an oversight, samples for 200 day strength were not cast for Unilit, but samples were tested at 120 days. The compressive strength for these samples was approximately 1,000 psi or 6.9 MPa.

¹⁰¹ Boynton, "Strength Considerations in Mortar," p. 4.

Splitting Tensile Strength

Tensile strength of the 3 types of hydrated hydraulic lime mortars were measured using ASTM's C 780 - 96 A8 Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens. Originally, ASTM's C 190 Standard Test Method for Tensile Strength of Hydraulic Cement Mortars was to be used and samples were made but the limitations of using the dog biscuit shaped samples prescribed for this test were learned of and this test was discarded. Apparently the dog biscuit shaped samples have the tendency to break in different places making results inconsistent and hard to reproduce.

Procedure

The specimens were 3" x 6" (76.2 x 152.4 mm) cylinders cast in single-use cardboard molds. Four specimens of each mortar type were made. Casting of more than 4 specimens per mortar was impossible because of the large volume of mortar required to fill the relatively large molds. The intent was to stay fairly uniform with the mix size throughout the experiments. Making a larger mortar batch would have deviated from this course. In hindsight 2" x 4" cylinder molds, which conform to the standard, would have been a better choice because they require less material. As a result the mortars were only tested for 28 day tensile strength. The test data for splitting tensile strength can be found in Appendix B.

The molds were lightly coated with mineral oil to minimize the mortar sticking to the sides of the molds. The mortar was placed in the molds in 3 layers of approximately the same depth. Each layer was spaded 20 times with the spatula in one complete revolution around the mold. In spading the second and third layers, care was taken to not penetrate the surface of the previous layer. The mold was overfilled for the final layer. The molds were taped lightly to remove air pockets, and any overflowing mortar was struck off with a straight edge.

All 3 mortars specimens were cast on the same day to minimize any affect of curing conditions. Laboratory conditions were $75^{\circ} \pm 2^{\circ}$ Fahrenheit and a relative humidity of $36\% \pm 2\%$.

The molds were covered with damp burlap, wrapped with plastic wrap and placed in a moist insulated cooler for storage. The samples remained in the cooler for 7 days. At that time they were removed, demolded and allowed to air-cure until 28 days.

The testing machine was Satec Systems, Incorporated, Prism Model MK III-C100 QC Compressive Strength Machine with an electronic control / digital indicator.

The specimen was placed horizontally on the load bearing plate of the machine and aligned. Small wooden wedges were used to hold the sample in place. The load was applied continuously at a rate within the range of 100 - 200 psi/min. until the specimen failed. The maximum applied load was recorded for each specimen as indicated by the machine.

Jura had the highest splitting tensile strength with 246 psi/ 1.70 MPa (13.3% of 28 day compressive strength), followed by Riverton with 104 psi/ 0.72 MPa (9.2% of 28 day compressive strength), and Unilit with 35 psi/ 0.24 MPa (5.9% of 28 day compressive strength). The Jura was more than 7 times the strength of the Unilit and 2.3 times the strength of Riverton. This is surprising considering the compressive strength differences, which finds Jura at 28 days approximately 3 times as strong as the Unilit and about 1 1/2 times as strong as the Riverton.

Water Vapor Transmission

Permeability is a material's ability to transmit a liquid or vapor through it. Good permeability is desired because it allows the masonry to breathe and dry out quickly. It is desired that the mortar have a higher vapor transmission rate than the masonry substrate. The mortar should act as a wick and draw the water away from the substrate and to the exterior

surface of the building, preventing the trapping of water behind the substrate. Good permeability may aid in freeze thaw resistance as well.

The test method followed for measuring permeability was developed by Judith Jacob and Norman Weiss and is called "Laboratory Measurement of Water Vapor Transmission Rates of Masonry Mortars and Paints" which was published in *APT Bulletin* Vol. XXI No. 3/4 1989. Jacob and Weiss based their testing on ASTM's E 96-80, "Standard Test Methods for Water Vapor Transmission of Materials."¹⁰²

The sample shape was a disc. The molds for the samples were petri dishes with an inside diameter of 3 1/2" and a height of 1/2". The inside of the molds were coated with a thin layer of mineral oil to act as a release agent to allow easier removal of the sample. The mortar was placed in the molds in 2 equal layers pressing the mortar with the thumbs approximately 32 times per layer, making sure to leave no voids. The excess or protruding mortar was cut away by drawing the straight edge of a trowel across the face of the specimen with a sawing motion; this left the mortar's plane surface flush with the top of the mold.

The samples were covered with a damp piece of burlap and the petri dish cover for the petri dish. The samples were left in their molds for a period of 7 days in an air-tight chamber. They were gently removed by pushing down with the thumbs in the middle of the petri dish and gripping the sides of the dish with the other fingers. The laitence were removed by brushing the bottom and top to expose the pore structure with a stiff bristle brush. This was completed after 28 days of curing. The average disc size was approximately 12 mm in depth by 86 mm in width.

¹⁰² Judith Jacob and Norman R. Weiss, "Laboratory Measurement of Water Vapor Transmission Rates of Masonry Mortars and Paints," *APT Bulletin, The Journal of Preservation Technology*, Volume XXI, NO. 3 & 4 (1989), pp. 62-70.

The discs outside edge were wrapped with 1/2" wide Neoprene closed-cell foam tape to act as an air tight barrier against the release of the water vapor. The tape was a self-sealing tape and was 1/4" thick. It is described by the manufacturer (Seal-King) as a "Low density, very aggressive foam sealant, used extensively in the automotive and other industries for permanently sealing against air, water, dust, vibrations, and noise".¹⁰³

Eight beakers were used of each mortar type, 7 were filled with 150 ml of water and 1 was left empty to serve as a control. The discs were placed firmly inside the beakers so that the top of the discs were even with the top of the beaker. The discs were placed in 500 ml polypropylene beakers which have a upper inner diameter of 75 mm. Starting at the top, the sides of the beakers gradually slope inward all the way to the base. The individual samples were marked by means of a permanent marker on the top of the mortar discs. The initial weight of the samples was taken and they were placed in the desiccating chamber.

The chamber consisted of a large 100 liter insulated cooler with inside dimensions measuring 3' in length, 1' in width, and a height of 16". The cooler made an ideal chamber because it was insulated, air tight, and because of its large size. The desiccant was changed daily to keep the relative humidity as low as possible. It was changed when the readings were taken for the measuring of the daily weight changes of the samples. One liter of desiccant was used in the chamber. The desiccant was dried in an oven at 120° C for a period of 6 hours.

The samples were weighed every 24 hours at approximately the same time, within a 1/2 hour, and the weights were recorded to the nearest 0.1g. The weights were taken for a period of 21 days. The data for vapor transmission is found in Appendix C1 - C5.

¹⁰³ Seal-King Foam Tape Sealant Product Literature.

Riverton hydraulic lime had the highest weight loss per day at of 0.61 grams per day over the 21 day period. Unilit had an average loss of 0.59 grams and Jura had a loss of 0.36 grams.

The vapor transmission test was repeated on the samples after 120 days had elapsed. The vapor transmission rates of all the hydraulic lime mortar types dropped appreciably from the age 28 day testing results. The Unilit now had the greatest weight change per day at an average of 0.47 g lost per day and a vapor transmission rate of 3.36. This equates to a 22% decrease in the vapor transmission rate.

The Riverton was now second in weight change with a loss of 0.46 g per day and a vapor transmission rate of 3.25. This is a 25% decrease for the Riverton from the 28 day rates.

The Jura had the least change in rates compared with its 28 day results, with a daily loss of 0.31 g and a vapor transmission rate of 2.18, which translates to a 15% decrease in vapor transmission rates.

The change in vapor transmission rates is remarkable considering the short period (90 days) that it took place in. It remains to be seen if this affects the performance of the mortars and if this effect is positive or negative. The rate change can probably be attributed to the decrease in pore space brought about by the continued crystalline formation. Of note, the decrease in vapor transmission rates correlates with an increase in compressive strength rates of the mortars.

Drying Shrinkage

The term drying shrinkage as defined as ASTM is as follows:

The decrease in length of the test specimen, measured along the longitudinal axis where the decrease is caused by any factor other than externally applied forces under stated conditions of temperature, relative humidity, and evaporation rate of the environment. The term includes the net effect of a variety of phenomena tending to bring about both increases and decreases in length during the period in which the test specimens under consideration are stored in the specified environment and in which a number of processes, including hydration of the cement, are taking place at a variety of rates.¹⁰⁴

The molds used were 25 mm by 25 mm by 285 mm (1" x 1" x 11 1/4") prism molds manufactured by Humboldt Manufacturing. In addition, the comparator was manufactured by Humboldt Manufacturing Co. of Chicago, IL (1-800-544-7220), model H-3250 Humboldt Volume Change Indicator (Comparator). Both the length comparator and the molds conformed with ASTM's C 490, Standard Practice for use of Apparatus for the Determination of Length Change of Hardened Cement Paste, Mortar, and Concrete.

The standard loosely followed for determining length change was ASTM C 596. This experiment deviated from the standard in that the specimens were not moist-cured in the molds for 24 hours, and cured in water for 48 hours. Instead, the specimens were covered with damp burlap and plastic wrap and the specimens were damp-cured in their molds for 72 hours in a insulated air-tight cooler. At 72 hours the specimens were removed and left to air-cure. Two batches of mortar were made of each mortar type, with a minimum of 4 specimens being made for each mortar batch.

Several specimens broke upon removal from the molds. This was due to the fragility of the specimens brought about by the shape of the specimens and was due to their extreme length and narrow width. The specimens often adhered to the sides and bottom of the mold. It was difficult to remove them from the mold without causing damage. The molds are more

¹⁰⁴ American Society for Testing and Materials, "C 596 Standard Test Method for Drying Shrinkage of Mortar Containing Portland Cement," *Annual Book of ASTM Standards*, Vol. 04.01, Cement; Lime; Gypsum, (Philadelphia: ASTM, 1987), p. 380.

appropriate for cement specimens due to their high strength, and is inadequate for lime mortar and other lower strength materials. Six test specimens of each mortar type were made.

Length comparator readings were taken at 3, 7, 14, 21, 28, and 120 days from the initial casting of the specimens. The average change in unit length was determined for each age of drying along with the average length. All readings were expressed in thousandths of an inch. The readings are recorded in Appendix D1 - D5. The results for length change after 120 days are as follows: Unilit lime shrank the least, decreasing in length an average of 0.0115" or 0.012%; Riverton decreased an average length of 0.0152" or 0.015%; and Jura decreased the most shrinking an average of 0.0162" or 0.016%.

Initially at the 7 day interval, all mortars shrank approximately 0.010". At the 14 day interval, the Jura shrank an additional 0.004% (total of 0.014%), the Riverton an additional 0.002% (overall total 0.012%), and the Unilit did not shrink at all for this time period (overall total of 0.010%).

For the 21 day length change, the Unilit was the only mortar to shrink, shrinking 0.001% (overall total of 0.011%). Neither the Jura or Riverton shrank. None of the mortars shrank between the 21 and 28 day time period.

Between the 28 day and the 120 day time period the Riverton shrank the most at 0.03%, the Jura shrank an additional 0.02%, and the Unilit shrank an additional 0.01%.

There seems to be a correlation between the strength of the mortars and the amount the mortars shrank. The strongest mortar, Jura shrank the most. Unilit the weakest mortar, shrank the least.

Absorption and Bulk Specific Gravity

ABSORPTION

The test method selected for measuring the absorption properties of the three mortar types was taken from ASTM C 97 - 83 (Reapproved 1988) Standard Test Method for Absorption and Bulk Specific Gravity of Dimension Stone.¹⁰⁵ The importance of absorption and bulk specific gravity is discussed in the section on porosity. This particular test measures the quantity of water absorbed by a material immersed in deionized water at room temperature and pressure, expressed as a percentage of the dry mass of the sample. The test aids in characterizing porous building materials. The test calls for the samples to be of a regular form such as cubes. It was suggested by ASTM that the specimens should not be less than 2" (50.8 mm) or more than 3" (76.2 mm) so that the value of the ratio of the surface to volume ratio should be between 0.3" (7.6 mm) and 0.5" (12.7 mm). The selected form was a cube of 2" (50.8 mm). The standard called for a minimum of 3 samples, which are similar as possible in physical properties and in condition. Four specimens of each mortar type were used. The mortars were damp-cured in their molds for 3 days and demolded and air-cured. The mortars cured for approximately 50 days before testing.

Procedure

The specimens were weighed prior to drying in an oven for a period of 24 hours at a temperature of $105 \pm 2^{\circ}$ C. They were allowed to cool in the lab for a period of 30 minutes and weighed. Immediately after weighing, the specimens were immersed completely in distilled water for a period of 48 hours at $20 \pm 5^{\circ}$ C. The container had a plastic grate on the bottom to

¹⁰⁵ American Society for Testing of Materials, "C 97 Standard Test Methods for Absorption and Bulk Specific Gravity of Dimension Stone," *Annual Book of ASTM Standards*, Vol. 04.08, Soil and Rock; Building Stones; Geotextiles, (Philadelphia: ASTM, 1988), p. 1.

expose all sides of the specimens directly with the water. At the end of 48 hours the specimens were removed and weighed individually. Prior to weighing, the specimens were surface dried with a damp cloth. The absorption and specific gravity data is recorded in Appendix E.

The specimens percentage of weight absorption was determined as follows:

Absorption, weight % = $[(B-A)/A] \times 100$

where A is equal to the weight of the dried specimen and B is equal to the weight of the specimen after immersion.¹⁰⁶

The three hydraulic lime mortars had similar absorption properties, with a difference of less than 1% in regards to weight increase. The Jura had the highest amount of water absorption with an average weight increase of 10.6%, followed by 9.8% for the Riverton, and 9.7% for the Unilit.

BULK SPECIFIC GRAVITY

The bulk specific gravity gives a convenient and accurate means of calculating the unit weight of a material. The same specimens that were used for measuring absorption were also used for measuring the bulk specific gravity. Four specimens were used from each mortar type.

Procedure

Immediately after the mortars were measured for absorption, the bulk specific gravity was determined. The saturated specimens were weighed by suspending them in a container of

¹⁰⁶ Ibid., p. 2.

distilled water. This was accomplished by placing the specimen in a wire basket which was hung from a balance. The basket and specimen were submerged in the water and weighed.¹⁰⁷

The three hydraulic mortars had similar bulk specific gravities. The Unilit mortar had the highest bulk specific gravity at 2.09, followed by Jura at 2.06, and Riverton at 1.98.

Salt Crystallization

The test method selected for weathering and salt resistance properties of the mortar types was taken from Teutonico.¹⁰⁸ The mortars were tested for a preliminary estimate of their resistance or soundness when subjected to weathering action by repeatedly immersing the samples in a saturated solution of sodium sulfate followed by oven drying the samples to completely dehydrate the salt which precipitated in permeable pore spaces. This internal expansive force, from the dehydration of the salt upon re-immersion, simulates the expansion of water on freezing. The test is a good indicator of the mortars resistance to salts either from salt which can be introduced through Portland cements, pollutants, or road salt.

Procedure

The samples were first dried in an oven for a period of 24 hours at 60° C and weighed for the initial weight (Mo). The samples were immersed in a 14% solution of sodium sulfate decahydrate for a period of 24 hours. The samples were removed and were placed in a drying oven at $60 \pm 5^{\circ}$ C for a period of 24 hours. One cycle consisted of 24 hours of immersion in the salt solution followed by 24 hours of drying in the oven.¹⁰⁹ A plastic, rectangular container was used for holding the samples and the salt solution. The container had a lid to cover it and

¹⁰⁷ Ibid.

¹⁰⁸ Jeanne Marie Teutonico, *A Laboratory Manual for Architectural Conservators*, (Rome: ICCROM, 1988), p. 57.

¹⁰⁹ Ibid.

prevent evaporation of the solution. The container also had a plastic mesh grid which was elevated a 1/2" from the bottom of the container. This allowed access for the solution to all sides of the samples and for any debris to fall to the bottom of the container.

Test samples consisted of 2" cubes. Four samples of each mortar type were used for the test. The samples were measured for weight change to the nearest 0.1 of a gram. The same electronic balance was used for all weighings throughout the experiment. After the samples had cooled to room temperature they were immersed in the solution. The samples were covered by at least a 1/2" of solution. This cycle of immersion and drying was repeated until the samples were destroyed. The weight changes are recorded in Appendix F.

The weight gain was caused by the absorption of the sodium sulfate solution. The weight loss was caused by the formation of salt crystals within the pores which exerts pressure upon the sample and causes spalling and deterioration of the sample.

The Unilit hydraulic mortar was the first to show signs of disintegration after only 2 cycles and all specimens were completely deteriorated by end of 4 cycles. The deterioration was quick and extensive for the Unilit specimens. The whole cube seemed to disintegrate to a pile of aggregate and binder, it did not break down into mortar chunks as with the others.

The Jura was the second to begin disintegrating after only 4 cycles and was completely deteriorated by 9 cycles. The Jura cracked and broke into large chunks which in turn further disintegrated.

The Riverton performed the best by far in this experiment lasting a total of 11 cycles before showing signs of deterioration and disintegrating after 12 cycles. The Riverton cubes showed little sign of deterioration up to the eleventh cycle, losing only a corner or two on a cube.

But at the eleventh cycle the specimens showed major signs of spalling of the surface. After this cycle the cubes quickly deteriorated.

This test may give unreliable results when aluminates are present in the cement. This is because the sulfates react with the aluminates in the hardened cementitious paste, especially the calcium aluminate hydrate, to form calcium sulphoaluminate (ettringite). The formation of crystals cause expansive reactions with sufficient enough pressure to crack and disintegrate the sample.¹¹⁰

Conclusion

Hydraulic lime was an important component in masonry construction in the nineteenth century. It may again become important; this time for the conservation and restoration masonry buildings.

When using a commercial hydraulic lime the product should be investigated. Considerations to take into account before the use of a hydraulic lime are: the geology of the limestone, the manner and temperature in which the material was burned, its chemical constituents, the possible presence of additives in the material, the physical properties of the material, and how and where the material is too be used. All of these factors play a major part in how the material will perform in situ.

In this study, the qualities, properties, and performance of a “restoration mortar” were reviewed. These properties must also be considered when selecting a material. The mortar must

¹¹⁰ Kosmatka, *Design and Control of Concrete*, p. 20.

be permeable, durable, have quality ingredients, properly installed and cured, similar in performance to the masonry substrate, and sacrificial to the masonry.

Three hydraulic limes properties and performance were examined in the second half of this study. The limes performed differently. Each had assets as well as faults. It is evident that it is not in good practice to generically specify the use of “a hydraulic lime” for a project as with a non-hydraulic lime. Hydraulic lime varies more from non-hydraulic lime in this respect. Non-hydraulic limes tend to perform similarly in a more specific range, where as with hydraulic limes the range is much broader. All three hydraulic limes show potential for use in restoration, and as well replacing Portland cement in restoration. A summary of the limes’ performances follows.

The Jura can be considered an eminently-hydraulic lime. Jura's properties included: high compressive and splitting tensile strength; low permeability; little drying shrinkage; had similar absorption and bulk specific gravity as the other mortars; and performed reasonably well in the salts crystallization test. Of some concern regarding the Jura is its low permeability and very high compressive strength. It therefore should probably not be used straight in a mortar mix on most historic buildings with weak or porous masonry substrate. Perhaps these problems could be alleviated by mixing the Jury with lime putty; which would increase the permeability and lower its strength. Another possible additive may be a high-fired brick dust to increase porosity. The last issue that needs to be resolved is that Jura's chemical composition is not known. It would be reassuring to know this information, especially considering its high strength and low permeability.

The Riverton can be considered an eminently-hydraulic lime. It's properties include a relatively high compressive strength; moderate to low tensile strength; good permeability; little drying shrinkage; similar absorption and bulk specific gravity to the other limes; very good durability in the salts crystallization test; and a good air content. Overall Riverton performed

very well. It appears that Riverton can be used for numerous applications, including those with extreme exposure. The one issue with Riverton is the consistency of the limestone. It has been said that there are strength fluctuations in the product from time to time.

The Unilit B-Fluid X can be considered a moderately-hydraulic lime. It had moderate compressive and splitting tensile strength; good permeability; little drying shrinkage; similar absorption and bulk specific gravity compared to the other limes; and poor resistance to the salt crystallization test. The Unilit shows promise as a mortar, especially with its high permeability. The Unilit may not be appropriate for areas that receive extreme exposure, but this can not be determined without further durability testing. To know the chemical composition for Unilit would be beneficial as well.

Hydraulic lime shows great promise for restoration and conservation of masonry. But there is still much too be learned about the material and its properties. This is in evidence with the many revisions to the European standards that are currently under way. There is a broad range of materials that are currently considered "hydraulic lime". More testing is needed for the long term performance and durability of the material. Until more is known about hydraulic limes, caution should be used when considering their use, as with any unfamiliar material.

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Appendix A1

COMPRESSIVE STRENGTH

| Jura | | sample 1 | sample 2 | sample 3 | sample 4 | sample 5 | Average | |
|-----------------|-----------------|----------|----------|----------|----------|----------|--------------|-----|
| 24 hours | | 331 | 361 | 340 | - | - | 344 | psi |
| | | 2.29 | 2.49 | 2.35 | - | - | 2.37 | MPa |
| 3 days | | 871 | 850 | 853 | - | - | 858 | psi |
| | | 6.01 | 5.87 | 5.88 | - | - | 5.92 | MPa |
| 7 days | | 1229 | 1200 | 1255 | 1264 | - | 1237 | psi |
| | | 8.48 | 8.28 | 8.66 | 8.72 | - | 8.53 | MPa |
| 28 days | | 1898 | 1856 | 1853 | 1811 | - | 1854 | psi |
| | | 13.09 | 12.81 | 12.78 | 12.50 | - | 12.80 | MPa |
| wet cure | 200 days | 3558 | 3565 | 3686 | - | - | 3603 | psi |
| | | 24.55 | 24.60 | 25.44 | - | - | 24.86 | MPa |
| dry cure | 200 days | 1996 | 2023 | 1946 | - | - | 1988 | psi |
| | | 13.77 | 13.96 | 13.43 | - | - | 13.72 | MPa |

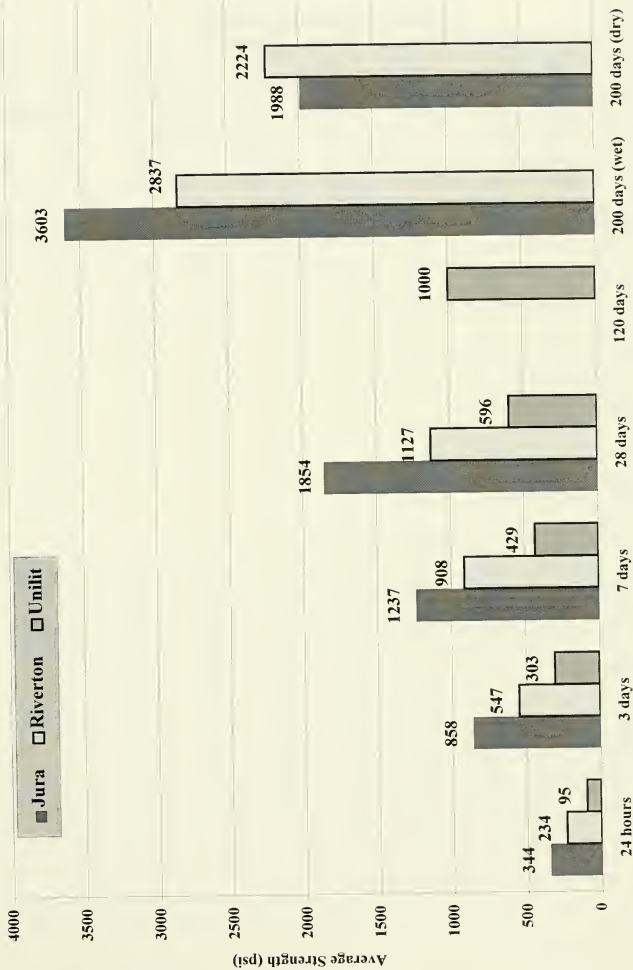
| Riverton | | sample 1 | sample 2 | sample 3 | sample 4 | sample 5 | Average | |
|-----------------|-----------------|----------|----------|----------|----------|----------|--------------|-----|
| 24 hours | | 228 | 226 | 248 | - | - | 234 | psi |
| | | 1.57 | 1.56 | 1.71 | - | - | 1.61 | MPa |
| 3 days | | 508 | 581 | 536 | 533 | 536 | 547 | psi |
| | | 3.50 | 4.01 | 3.70 | 3.67 | 3.70 | 3.69 | MPa |
| 7 days | | 901 | 915 | 909 | - | - | 908 | psi |
| | | 6.22 | 6.31 | 6.27 | - | - | 6.27 | MPa |
| 28 days | | 1150 | 1105 | 1106 | 1148 | - | 1127 | psi |
| | | 7.94 | 7.62 | 7.63 | 7.92 | - | 7.78 | MPa |
| wet cure | 200 days | 2813 | 2849 | 2849 | - | - | 2837 | psi |
| | | 19.41 | 19.66 | 19.66 | - | - | 19.57 | MPa |
| dry cure | 200 days | 2168 | 2321 | 2184 | - | - | 2224 | psi |
| | | 14.96 | 16.02 | 15.07 | - | - | 15.35 | MPa |

| Unilit | | sample 1 | sample 2 | sample 3 | sample 4 | sample 5 | Average | |
|-----------------|--|----------|----------|----------|----------|----------|-------------|-----|
| 24 hours | | 94 | 101 | 90 | - | - | 95 | psi |
| | | 0.65 | 0.70 | 0.62 | - | - | 0.66 | MPa |
| 3 days | | 275 | 295 | 313 | 330 | - | 303 | psi |
| | | 1.90 | 2.04 | 2.16 | 2.28 | - | 2.09 | MPa |
| 7 days | | 386 | 444 | 439 | 446 | - | 429 | psi |
| | | 2.67 | 3.06 | 3.03 | 3.08 | - | 2.96 | MPa |
| 28 days | | 605 | 623 | 590 | 566 | - | 596 | psi |
| | | 4.17 | 4.30 | 4.07 | 3.91 | - | 4.11 | MPa |

* All samples damp cured in molds for 3 days

* 28 day samples stored in water between the ages of 7 & 28 days

Compressive Strength



Appendix B

SPLITTING TENSILE STRENGTH

| | | 28 DAY TENSILE STRENGTH | | | | |
|-----------------|-----|-------------------------|----------|-------------|-------------|-----|
| | | sample 1 | sample 2 | sample 4 | Average | |
| Jura | psi | 259 | 233 | 84 | 246 | psi |
| | MPa | 1.79 | 1.61 | <i>0.58</i> | 1.70 | MPa |
| Riverton | psi | 109 | 88 | 49 | 104 | psi |
| | MPa | 0.75 | 0.61 | <i>0.34</i> | 0.72 | MPa |
| Unilit | psi | 33 | 33 | 36 | 35 | psi |
| | MPa | 0.23 | 0.22 | 0.25 | 0.24 | MPa |

*Numbers in italic indicate results that were discarded because of large variation from average

Appendix C1

JURA VAPOR TRANSMISSION

28 Day Vapor Transmission Rate

| day | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | avg 1-7 | avg loss | WVT |
|-------------|-------|-------|-------|-------|-------|-------|-------|-------|---------|----------|------|
| 1 | 343.7 | 342.5 | 346.7 | 341.9 | 346.7 | 341.0 | 342.4 | 192.2 | 343.56 | - | - |
| 2 | 343.4 | 342.2 | 346.4 | 341.7 | 346.5 | 340.8 | 342.2 | 192.1 | 343.31 | 0.24 | 1.72 |
| 3 | 343.0 | 341.8 | 346.0 | 341.2 | 346.0 | 340.3 | 341.7 | 191.8 | 342.86 | 0.46 | 3.24 |
| 4 | 342.6 | 341.4 | 345.6 | 340.8 | 345.6 | 339.9 | 341.3 | 191.7 | 342.46 | 0.40 | 2.84 |
| 5 | 342.3 | 341.0 | 345.3 | 340.4 | 345.3 | 339.5 | 341.0 | 191.6 | 342.11 | 0.34 | 2.43 |
| 6 | 342.0 | 340.6 | 344.9 | 340.0 | 344.9 | 339.1 | 340.6 | 191.5 | 341.73 | 0.39 | 2.74 |
| 7 | 341.6 | 340.3 | 344.6 | 339.7 | 344.5 | 338.8 | 340.2 | 191.5 | 341.39 | 0.34 | 2.43 |
| 8 | 341.3 | 339.9 | 344.3 | 339.3 | 344.2 | 338.4 | 339.9 | 191.5 | 341.04 | 0.34 | 2.43 |
| 9 | 341.0 | 339.5 | 343.9 | 338.9 | 343.8 | 338.1 | 339.5 | 191.4 | 340.67 | 0.37 | 2.64 |
| 10 | 340.6 | 339.2 | 343.6 | 338.6 | 343.5 | 337.7 | 339.2 | 191.4 | 340.34 | 0.33 | 2.33 |
| 11 | 340.3 | 338.8 | 343.2 | 338.2 | 343.1 | 337.3 | 338.8 | 191.4 | 339.96 | 0.39 | 2.74 |
| 12 | 340.0 | 338.4 | 342.9 | 337.8 | 342.7 | 337.0 | 338.4 | 191.4 | 339.60 | 0.36 | 2.54 |
| 13 | 339.6 | 338.1 | 342.6 | 337.4 | 342.4 | 336.6 | 338.1 | 191.4 | 339.26 | 0.34 | 2.43 |
| 14 | 339.3 | 337.7 | 342.2 | 337.0 | 342.0 | 336.2 | 337.8 | 191.4 | 338.89 | 0.37 | 2.64 |
| 15 | 338.9 | 337.3 | 341.8 | 336.6 | 341.6 | 335.8 | 337.3 | 191.4 | 338.47 | 0.41 | 2.94 |
| 16 | 338.7 | 337.0 | 341.6 | 336.3 | 341.4 | 335.6 | 337.1 | 191.4 | 338.24 | 0.23 | 1.62 |
| 17 | 338.3 | 336.7 | 341.3 | 336.0 | 341.0 | 335.2 | 336.7 | 191.4 | 337.89 | 0.36 | 2.54 |
| 18 | 338.0 | 336.3 | 340.9 | 335.5 | 340.6 | 334.8 | 336.3 | 191.4 | 337.49 | 0.40 | 2.84 |
| 19 | 337.6 | 335.9 | 340.6 | 335.2 | 340.2 | 334.4 | 335.9 | 191.4 | 337.11 | 0.37 | 2.64 |
| 20 | 337.2 | 335.5 | 340.2 | 334.8 | 339.9 | 334.0 | 335.6 | 191.4 | 336.74 | 0.37 | 2.64 |
| 21 | 336.9 | 335.1 | 339.8 | 334.4 | 339.5 | 333.6 | 335.2 | 191.3 | 336.36 | 0.39 | 2.74 |
| 21 day avg. | | | | | | | | | | 0.36 | 2.56 |

120 Day Vapor Transmission Rate

| day | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | avg 1-7 | avg loss | WVT |
|-------------|-------|-------|-------|-------|-------|-------|-------|-------|---------|----------|------|
| 1 | 324.2 | 321.2 | 326.9 | 319.9 | 326.0 | 319.5 | 321.4 | 192.5 | 322.73 | - | - |
| 2 | 323.9 | 320.9 | 326.5 | 319.5 | 325.6 | 319.2 | 321.0 | 192.4 | 322.37 | 0.36 | 2.54 |
| 3 | 323.6 | 320.6 | 326.3 | 319.2 | 325.3 | 318.8 | 320.7 | 192.3 | 322.07 | 0.30 | 2.13 |
| 4 | 323.3 | 320.2 | 326.0 | 318.8 | 325.0 | 318.5 | 320.4 | 192.3 | 321.74 | 0.33 | 2.33 |
| 5 | 323.1 | 319.9 | 325.7 | 318.5 | 324.7 | 318.2 | 320.1 | 192.2 | 321.46 | 0.29 | 2.03 |
| 6 | 322.7 | 319.6 | 325.4 | 318.2 | 324.4 | 317.9 | 319.8 | 192.2 | 321.14 | 0.31 | 2.23 |
| 7 | 322.5 | 319.3 | 325.1 | 317.8 | 324.1 | 317.6 | 319.5 | 192.2 | 320.84 | 0.30 | 2.13 |
| 8 | 322.2 | 319.0 | 324.8 | 317.5 | 323.8 | 317.3 | 319.2 | 192.3 | 320.54 | 0.30 | 2.13 |
| 9 | 321.9 | 318.7 | 324.5 | 317.2 | 323.5 | 317.0 | 318.9 | 192.3 | 320.24 | 0.30 | 2.13 |
| 10 | 321.6 | 318.4 | 324.2 | 316.9 | 323.2 | 316.6 | 318.6 | 192.3 | 319.93 | 0.31 | 2.23 |
| 11 | 321.4 | 318.0 | 323.9 | 316.6 | 322.9 | 316.3 | 318.2 | 192.2 | 319.61 | 0.31 | 2.23 |
| 12 | 321.1 | 317.7 | 323.7 | 316.3 | 322.6 | 316.0 | 318.0 | 192.3 | 319.34 | 0.27 | 1.93 |
| 11 day avg. | | | | | | | | | | 0.31 | 2.18 |

* All weights measured in grams

te or WVT = weight change in grams

ht change in g; t = time in hours, A_i = cup mouth area, m²

Appendix C2

RIVERTON VAPOR TRANSMISSION

28 Day Vapor Transmission Rate

| day | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | avg 1-7 | avg loss | WVT |
|-------------|-------|-------|-------|-------|-------|-------|-------|-------|---------|----------|------|
| 1 | 327.8 | 328.9 | 326.6 | 330.8 | 326.5 | 333.6 | 331.1 | 178.3 | 329.33 | - | - |
| 2 | 327.4 | 328.5 | 326.2 | 330.4 | 326.1 | 333.2 | 330.7 | 178.1 | 328.93 | 0.40 | 2.84 |
| 3 | 326.7 | 327.8 | 325.5 | 329.6 | 325.3 | 332.5 | 329.9 | 177.9 | 328.19 | 0.74 | 5.27 |
| 4 | 326.0 | 327.2 | 324.9 | 329.0 | 324.7 | 331.9 | 329.3 | 177.8 | 327.57 | 0.61 | 4.36 |
| 5 | 325.3 | 326.5 | 324.3 | 328.4 | 324.0 | 331.2 | 328.6 | 177.7 | 326.90 | 0.67 | 4.77 |
| 6 | 324.7 | 326.0 | 323.7 | 327.8 | 323.4 | 330.6 | 328.0 | 177.7 | 326.31 | 0.59 | 4.16 |
| 7 | 324.2 | 325.3 | 323.1 | 327.2 | 322.8 | 330.0 | 327.4 | 177.7 | 325.71 | 0.60 | 4.26 |
| 8 | 323.5 | 324.8 | 322.6 | 326.6 | 322.2 | 329.5 | 326.8 | 177.7 | 325.14 | 0.57 | 4.06 |
| 9 | 322.9 | 324.2 | 322.0 | 326.0 | 321.5 | 328.8 | 326.1 | 177.7 | 324.50 | 0.64 | 4.56 |
| 10 | 322.3 | 323.6 | 321.4 | 325.4 | 321.0 | 328.3 | 325.5 | 177.7 | 323.93 | 0.57 | 4.06 |
| 11 | 321.7 | 323.0 | 320.8 | 324.8 | 320.3 | 327.7 | 324.9 | 177.7 | 323.31 | 0.61 | 4.36 |
| 12 | 321.1 | 322.4 | 320.2 | 324.2 | 319.7 | 327.1 | 324.3 | 177.7 | 322.71 | 0.60 | 4.26 |
| 13 | 320.4 | 321.8 | 319.6 | 323.6 | 319.1 | 326.5 | 323.6 | 177.7 | 322.09 | 0.63 | 4.46 |
| 14 | 319.7 | 321.1 | 319.0 | 323.0 | 318.4 | 325.9 | 323.0 | 177.7 | 321.44 | 0.64 | 4.56 |
| 15 | 319.1 | 320.5 | 318.4 | 322.3 | 317.8 | 325.3 | 322.4 | 177.7 | 320.83 | 0.61 | 4.36 |
| 16 | 318.6 | 320.1 | 317.9 | 321.9 | 317.3 | 324.8 | 321.8 | 177.7 | 320.34 | 0.49 | 3.45 |
| 17 | 318.0 | 319.4 | 317.3 | 321.2 | 316.6 | 324.2 | 321.2 | 177.7 | 319.70 | 0.64 | 4.56 |
| 18 | 317.3 | 318.8 | 316.7 | 320.6 | 316.0 | 323.6 | 320.6 | 177.7 | 319.09 | 0.61 | 4.36 |
| 19 | 316.7 | 318.2 | 316.1 | 320.0 | 315.3 | 323.0 | 319.9 | 177.7 | 318.46 | 0.63 | 4.46 |
| 20 | 316.1 | 317.6 | 315.5 | 319.4 | 314.7 | 322.4 | 319.3 | 177.7 | 317.86 | 0.60 | 4.26 |
| 21 | 315.3 | 316.9 | 314.9 | 318.7 | 314.0 | 321.7 | 318.6 | 177.7 | 317.16 | 0.70 | 4.97 |
| 21 day avg. | | | | | | | | | | 0.61 | 4.32 |

120 Day Vapor Transmission Rate

| day | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | avg 1-7 | avg loss | WVT |
|-----------|-------|-------|-------|-------|-------|-------|-------|-------|---------|----------|------|
| 1 | 293.7 | 295.7 | 293.9 | 297.5 | 292.7 | 301.3 | 296.5 | 179.9 | 295.90 | - | - |
| 2 | 293.2 | 295.2 | 293.5 | 297.0 | 292.2 | 300.9 | 296.0 | 179.7 | 295.43 | 0.47 | 3.35 |
| 3 | 292.7 | 294.8 | 293.0 | 296.5 | 291.8 | 300.4 | 295.5 | 179.7 | 294.96 | 0.47 | 3.35 |
| 4 | 292.3 | 294.3 | 292.6 | 296.0 | 291.3 | 299.9 | 295.0 | 179.6 | 294.49 | 0.47 | 3.35 |
| 5 | 291.8 | 293.9 | 292.1 | 295.6 | 290.8 | 299.5 | 294.6 | 179.6 | 294.04 | 0.44 | 3.14 |
| 6 | 291.3 | 293.4 | 291.7 | 295.1 | 290.3 | 299.0 | 294.1 | 179.6 | 293.56 | 0.49 | 3.45 |
| 7 | 290.9 | 292.9 | 291.2 | 294.7 | 289.9 | 298.6 | 293.6 | 179.6 | 293.11 | 0.44 | 3.14 |
| 8 | 290.4 | 292.5 | 290.8 | 294.2 | 289.4 | 298.2 | 293.2 | 179.6 | 292.67 | 0.44 | 3.14 |
| 9 | 289.9 | 292.0 | 290.4 | 293.8 | 288.9 | 297.7 | 292.7 | 179.6 | 292.20 | 0.47 | 3.35 |
| 10 | 289.4 | 291.4 | 289.9 | 293.3 | 288.5 | 297.2 | 292.2 | 179.6 | 291.70 | 0.50 | 3.55 |
| 11 | 289.0 | 291.1 | 289.5 | 292.8 | 288.0 | 296.8 | 291.7 | 179.6 | 291.27 | 0.43 | 3.04 |
| 12 | 288.6 | 290.7 | 289.1 | 292.4 | 287.5 | 296.4 | 291.3 | 179.7 | 290.86 | 0.41 | 2.94 |
| 11 day av | | | | | | | | | | 0.46 | 3.25 |

* All weights measured in grams

Water Vapor Transmission Rate or WVT = weight change in grams

G = weight change in g; t = time in hours, h; A = cup mouth area, m²

Appendix C3

UNILIT VAPOR TRANSMISSION

28 Day Vapor Transmission Rate

| day | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | avg 1- 7 | avg loss | WVT |
|-------------|-------|-------|-------|-------|-------|-------|-------|-------|----------|----------|------|
| 1 | 341.6 | 340.2 | 340.9 | 339.2 | 341.2 | 345.4 | 343.7 | 190.6 | 341.74 | - | - |
| 2 | 341.2 | 339.7 | 340.5 | 338.8 | 340.8 | 344.9 | 343.2 | 190.5 | 341.3 | 0.44 | 3.14 |
| 3 | 340.5 | 339.0 | 339.8 | 338.1 | 340.1 | 344.3 | 342.5 | 190.4 | 340.61 | 0.69 | 4.87 |
| 4 | 339.9 | 338.4 | 339.2 | 337.5 | 339.5 | 343.7 | 341.9 | 190.3 | 340.01 | 0.60 | 4.26 |
| 5 | 339.3 | 337.8 | 338.7 | 336.9 | 339.0 | 343.1 | 341.3 | 190.3 | 339.44 | 0.57 | 4.06 |
| 6 | 338.7 | 337.2 | 338.1 | 336.3 | 338.4 | 342.5 | 340.7 | 190.3 | 338.84 | 0.60 | 4.26 |
| 7 | 338.1 | 336.6 | 337.6 | 335.8 | 337.8 | 341.9 | 340.0 | 190.3 | 338.26 | 0.59 | 4.16 |
| 8 | 337.5 | 336.0 | 337.0 | 335.2 | 337.3 | 341.4 | 339.4 | 190.3 | 337.69 | 0.57 | 4.06 |
| 9 | 337.0 | 335.4 | 336.5 | 334.6 | 336.7 | 340.8 | 338.8 | 190.3 | 337.11 | 0.57 | 4.06 |
| 10 | 336.4 | 334.8 | 335.9 | 334.0 | 336.2 | 340.2 | 338.2 | 190.3 | 336.53 | 0.59 | 4.16 |
| 11 | 335.8 | 334.2 | 335.4 | 333.4 | 335.6 | 339.6 | 337.6 | 190.3 | 335.94 | 0.59 | 4.16 |
| 12 | 335.2 | 333.3 | 334.8 | 332.8 | 335.1 | 339.1 | 337.0 | 190.3 | 335.33 | 0.61 | 4.36 |
| 13 | 334.6 | 332.6 | 334.2 | 332.2 | 334.5 | 338.4 | 336.4 | 190.3 | 334.70 | 0.63 | 4.46 |
| 14 | 334.0 | 331.9 | 333.6 | 331.6 | 333.9 | 337.9 | 335.7 | 190.3 | 334.09 | 0.61 | 4.36 |
| 15 | 333.4 | 331.3 | 333.1 | 331.0 | 333.3 | 337.3 | 335.1 | 190.3 | 333.50 | 0.59 | 4.16 |
| 16 | 332.9 | 330.8 | 332.6 | 330.5 | 332.9 | 336.8 | 334.6 | 190.3 | 333.01 | 0.49 | 3.45 |
| 17 | 332.3 | 330.2 | 331.3 | 330.0 | 332.4 | 336.2 | 334.1 | 190.3 | 332.36 | 0.66 | 4.66 |
| 18 | 331.7 | 329.6 | 330.6 | 329.4 | 331.7 | 335.6 | 333.4 | 190.3 | 331.71 | 0.64 | 4.56 |
| 19 | 331.2 | 329.0 | 330.0 | 328.8 | 331.2 | 335 | 332.8 | 190.3 | 331.14 | 0.57 | 4.06 |
| 20 | 330.6 | 328.4 | 329.4 | 328.2 | 330.6 | 334.5 | 332.1 | 190.3 | 330.54 | 0.60 | 4.26 |
| 21 | 329.9 | 327.7 | 328.8 | 327.5 | 330 | 333.8 | 331.5 | 190.3 | 329.89 | 0.66 | 4.66 |
| 21 day avg. | | | | | | | | | | 0.60 | 4.29 |

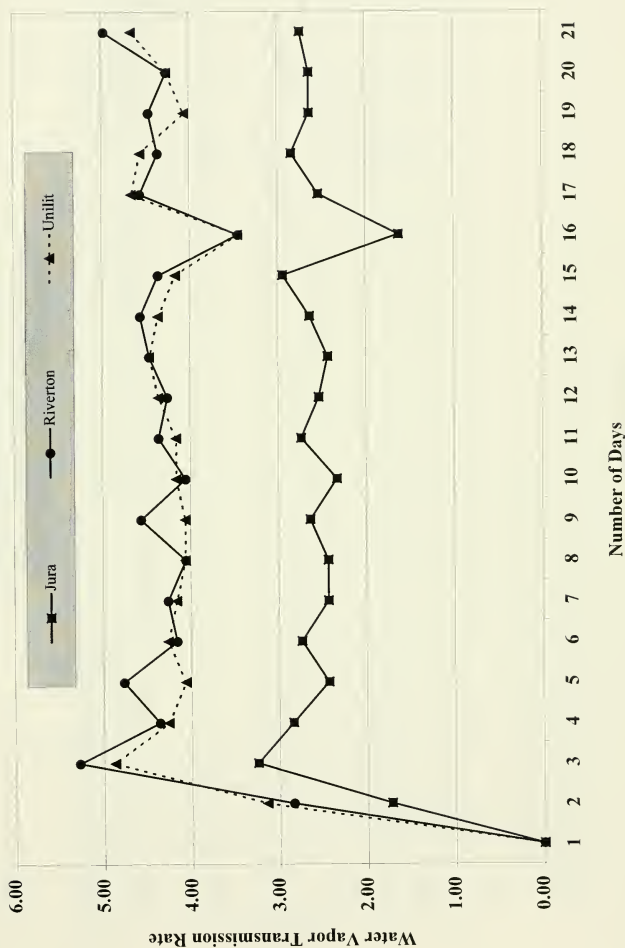
120 Day Vapor Transmission Rate

| day | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | avg 1- 7 | avg loss | WVT |
|-------------|-------|-------|-------|-------|-------|-------|-------|-------|----------|----------|------|
| 1 | 306.4 | 304.3 | 306.2 | 304.8 | 307.8 | 311.7 | 306.8 | 191.3 | 306.86 | - | - |
| 2 | 305.9 | 303.8 | 305.7 | 304.3 | 307.3 | 311.8 | 306.3 | 191.2 | 306.44 | 0.41 | 2.94 |
| 3 | 305.4 | 303.4 | 305.3 | 303.9 | 306.9 | 310.7 | 305.8 | 191.2 | 305.91 | 0.53 | 3.75 |
| 4 | 304.9 | 302.9 | 304.9 | 303.4 | 306.4 | 310.3 | 305.3 | 191.2 | 305.44 | 0.47 | 3.35 |
| 5 | 304.5 | 302.4 | 304.4 | 302.9 | 306.0 | 309.8 | 304.8 | 191.1 | 304.97 | 0.47 | 3.35 |
| 6 | 304.0 | 301.9 | 304.0 | 302.5 | 305.5 | 309.4 | 304.3 | 191.1 | 304.51 | 0.46 | 3.24 |
| 7 | 303.5 | 301.4 | 303.5 | 302.0 | 305.0 | 308.9 | 303.8 | 191.2 | 304.01 | 0.50 | 3.55 |
| 8 | 303.1 | 301.0 | 303.1 | 301.6 | 304.6 | 308.4 | 303.3 | 191.1 | 303.59 | 0.43 | 3.04 |
| 9 | 302.6 | 300.5 | 302.7 | 301.1 | 304.2 | 308.0 | 302.8 | 191.2 | 303.13 | 0.46 | 3.24 |
| 10 | 302.1 | 300.0 | 302.0 | 300.6 | 303.7 | 307.5 | 302.3 | 191.3 | 302.60 | 0.53 | 3.75 |
| 11 | 301.6 | 299.5 | 301.7 | 300.2 | 303.2 | 307.0 | 301.8 | 191.1 | 302.14 | 0.46 | 3.24 |
| 12 | 301.2 | 299.1 | 301.3 | 299.7 | 302.8 | 306.6 | 301.3 | 191.2 | 301.71 | 0.43 | 3.04 |
| 11 day avg. | | | | | | | | | | 0.47 | 3.36 |

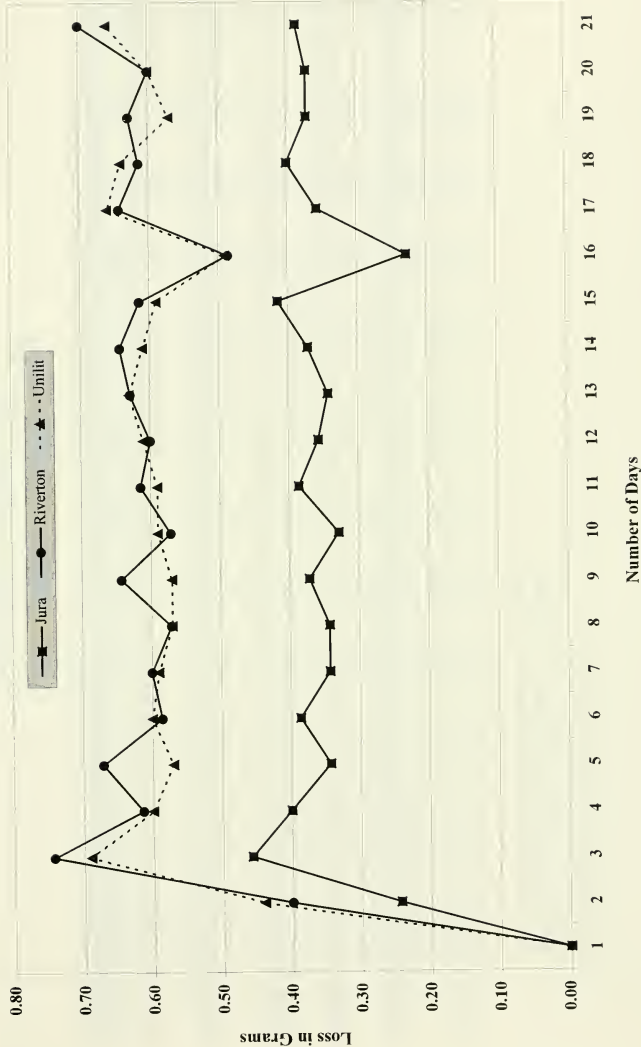
* All weights measured in grams

Water Vapor Transmission Rate or WVT = weight change in grams
 G = weight change in g; t = time in hours,h; A = cup mouth area, m2

Water Vapor Transmission



Average Daily Weight Loss



Appendix D1

DRYING SHRINKAGE

JURA HYDRAULIC LIME MORTAR

| Day | Sample 1 | Sample 2 | Sample 3 | Sample 4 | Sample 5 | Sample 6 | Sample 7 | Sample 8 | Sample 9 | Sample 10 | Sample 11 | Average |
|--------------|----------|----------|----------|----------|----------|----------|----------|----------|----------|-----------|-----------|----------|
| 3 | 0.1784 | 0.1400 | 0.1351 | 0.2091 | 0.1917 | 0.1906 | 0.1515 | 0.1673 | 0.1635 | 0.1565 | 0.1559 | 0.1672 |
| Li | -0.0216 | -0.0600 | -0.0649 | 0.0091 | -0.0081 | -0.0094 | -0.0485 | -0.0327 | -0.0365 | -0.0435 | -0.0441 | -0.0328 |
| 7 | 0.1676 | 0.1289 | 0.1251 | 0.1987 | 0.1807 | 0.1793 | 0.1416 | 0.1568 | 0.1550 | 0.1484 | 0.1472 | 0.1572 |
| Lx | -0.0324 | -0.0711 | -0.0749 | -0.0013 | -0.0193 | -0.0207 | -0.0584 | -0.0432 | -0.045 | -0.0516 | -0.0528 | -0.0428 |
| L | -0.0111% | -0.0111% | -0.0109% | -0.0109% | -0.0111% | -0.0111% | -0.0109% | -0.0111% | -0.0099% | -0.0089% | -0.0099% | -0.0101% |
| 14 | 0.1656 | 0.1262 | 0.1217 | 0.1954 | 0.1772 | 0.1763 | 0.1384 | 0.1524 | 0.1497 | 0.1419 | 0.1425 | 0.1534 |
| Lx | -0.0344 | -0.0738 | -0.0783 | -0.0046 | -0.0228 | -0.0237 | -0.0616 | -0.0476 | -0.0503 | -0.0581 | -0.0575 | -0.0466 |
| L | -0.013% | -0.014% | -0.013% | -0.014% | -0.015% | -0.014% | -0.013% | -0.015% | -0.014% | -0.015% | -0.013% | -0.014% |
| 21 | 0.1648 | 0.1253 | 0.1214 | 0.1944 | 0.1767 | 0.1758 | 0.1380 | 0.1519 | 0.1494 | 0.1414 | 0.1422 | 0.1528 |
| Lx | -0.0352 | -0.0747 | -0.0786 | -0.0056 | -0.0233 | -0.0242 | -0.062 | -0.0481 | -0.0506 | -0.0586 | -0.0578 | -0.0472 |
| L | -0.014% | -0.015% | -0.014% | -0.015% | -0.015% | -0.015% | -0.014% | -0.015% | -0.014% | -0.015% | -0.014% | -0.014% |
| 28 | 0.1648 | 0.1253 | 0.1214 | 0.1944 | 0.1766 | 0.1758 | 0.1380 | 0.1516 | 0.1492 | 0.1414 | 0.1421 | 0.1528 |
| Lx | -0.0352 | -0.0747 | -0.0786 | -0.0056 | -0.0234 | -0.0242 | -0.0620 | -0.0484 | -0.0508 | -0.0586 | -0.0579 | -0.0472 |
| L | -0.014% | -0.015% | -0.014% | -0.015% | -0.015% | -0.015% | -0.014% | -0.016% | -0.014% | -0.015% | -0.014% | -0.014% |
| 120 | 0.1633 | 0.1235 | 0.1196 | 0.1925 | 0.1752 | 0.1739 | 0.1363 | 0.1497 | 0.1475 | 0.1395 | 0.1403 | 0.1510 |
| Lx | -0.0367 | -0.0765 | -0.0804 | -0.0075 | -0.0248 | -0.0261 | -0.0637 | -0.0503 | -0.0525 | -0.0605 | -0.0597 | -0.0490 |
| L | -0.015% | -0.017% | -0.016% | -0.017% | -0.017% | -0.017% | -0.015% | -0.018% | -0.016% | -0.017% | -0.016% | -0.016% |
| total change | -0.0151 | -0.0165 | -0.0155 | -0.0166 | -0.0165 | -0.0167 | -0.0152 | -0.0176 | -0.0160 | -0.0170 | -0.0156 | -0.0162 |

Average Length Change 120 Day Period = -0.0451

Average % Shrinkage 120 Day Period = -0.016%

*Measurements in thousandths of an inch

Appendix D2

DRYING SHRINKAGE RIVERTON HYDRAULIC LIME MORTAR

| Day | Sample 1 | Sample 2 | Sample 3 | Sample 4 | Sample 5 | Sample 6 | Sample 7 | Sample 8 | Sample 9 | ample 10 | ample 11 | Sample 1 | Average |
|-------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|---------|
| 3 | 0.1463 | 0.1498 | 0.1622 | 0.1513 | 0.1877 | 0.1356 | 0.1410 | 0.2263 | 0.1580 | 0.1514 | 0.1517 | 0.2317 | 0.1661 |
| Li | -0.0537 | -0.0502 | -0.0378 | -0.0487 | -0.0123 | -0.0644 | -0.0590 | 0.0263 | -0.042 | -0.0486 | -0.0483 | 0.0317 | -0.0339 |
| 7 | 0.1363 | 0.1401 | 0.1518 | 0.1419 | 0.1778 | 0.1260 | 0.1318 | 0.2163 | 0.1470 | 0.1405 | 0.1446 | 0.2200 | 0.1562 |
| Lx | -0.0637 | -0.0599 | -0.0482 | -0.0581 | -0.0222 | -0.0740 | -0.0682 | 0.0163 | -0.053 | -0.0595 | -0.0554 | 0.0200 | -0.0438 |
| L | -0.010% | -0.010% | -0.010% | -0.009% | -0.010% | -0.010% | -0.009% | -0.010% | -0.011% | -0.011% | -0.007% | -0.012% | -0.010% |
| 14 | 0.1343 | 0.1380 | 0.1497 | 0.1396 | 0.1756 | 0.1238 | 0.1296 | 0.2143 | 0.1455 | 0.1390 | 0.1427 | 0.2184 | 0.1542 |
| Lx | -0.0657 | -0.0620 | -0.0503 | -0.0604 | -0.0244 | -0.0762 | -0.0704 | 0.0143 | -0.0545 | -0.061 | -0.0573 | 0.0184 | -0.0458 |
| L | -0.012% | -0.012% | -0.013% | -0.012% | -0.012% | -0.012% | -0.011% | -0.012% | -0.013% | -0.012% | -0.009% | -0.013% | -0.012% |
| 21 | 0.1339 | 0.1378 | 0.1492 | 0.1391 | 0.1752 | 0.1234 | 0.1293 | 0.2140 | 0.1454 | 0.1383 | 0.1420 | 0.2178 | 0.1538 |
| Lx | -0.0661 | -0.0622 | -0.0508 | -0.0609 | -0.0248 | -0.0766 | -0.0707 | 0.014 | -0.0546 | -0.0617 | -0.058 | 0.0178 | -0.0462 |
| L | -0.012% | -0.012% | -0.013% | -0.012% | -0.013% | -0.012% | -0.012% | -0.012% | -0.013% | -0.013% | -0.010% | -0.014% | -0.012% |
| 28 | 0.1337 | 0.1376 | 0.1491 | 0.1390 | 0.1750 | 0.1232 | 0.1291 | 0.2138 | 0.1448 | 0.1383 | 0.1420 | 0.2179 | 0.1536 |
| Lx | -0.0663 | -0.0624 | -0.0509 | -0.061 | -0.025 | -0.0768 | -0.0709 | 0.0138 | -0.0552 | -0.0617 | -0.058 | 0.0179 | -0.0464 |
| L | -0.013% | -0.012% | -0.013% | -0.012% | -0.013% | -0.012% | -0.012% | -0.013% | -0.013% | -0.013% | -0.010% | -0.014% | -0.012% |
| 120 | 0.1308 | 0.1347 | 0.1460 | 0.1361 | 0.1721 | 0.1203 | 0.1262 | 0.2109 | 0.1420 | 0.1357 | 0.1394 | 0.2156 | 0.1508 |
| Lx | -0.0692 | -0.0653 | -0.054 | -0.0639 | -0.0279 | -0.0797 | -0.0738 | 0.0109 | -0.0580 | -0.0643 | -0.0606 | 0.0156 | -0.0492 |
| L | -0.016% | -0.015% | -0.016% | -0.015% | -0.016% | -0.015% | -0.015% | -0.015% | -0.016% | -0.016% | -0.012% | -0.016% | -0.015% |
| total | -0.016% | -0.015% | -0.016% | -0.015% | -0.016% | -0.015% | -0.015% | -0.015% | -0.016% | -0.016% | -0.012% | -0.016% | -0.015% |
| | 0.0155 | 0.0151 | 0.0162 | 0.0152 | 0.0156 | 0.0153 | 0.0148 | 0.0154 | 0.0160 | 0.0157 | 0.0123 | 0.0161 | 0.0152 |

Average Length Change 120 Day Period = 0.0109

Average % Shrinkage 120 Day Period = -0.015%

*Measurements in thousandths of an inch

Appendix D3

DRYING SHRINKAGE

UNILIT HYDRAULIC LIME MORTAR

| Day | Sample 1 | Sample 2 | Sample 3 | Sample 4 | Sample 5 | Sample 6 | Sample 7 | Sample 8 | Sample 9 | Sample 10 | Sample 11 | Sample 12 | Sample 13 | Sample 14 | Sample 15 | Average |
|--------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|---------|
| 3 (Li) | 0.1794 | 0.1527 | 0.1253 | 0.1321 | 0.1383 | 0.1473 | 0.1047 | 0.2078 | 0.0868 | 0.1514 | 0.1515 | 0.1969 | 0.2419 | 0.1354 | 0.1834 | 0.1557 |
| Li | -0.0206 | -0.0473 | -0.0747 | -0.0679 | -0.0617 | -0.0527 | -0.0953 | 0.0078 | -0.1132 | -0.0486 | -0.0485 | -0.0031 | 0.0419 | -0.0646 | -0.0166 | -0.0443 |
| 7 | 0.1695 | 0.1430 | 0.1150 | 0.1213 | 0.1291 | 0.1368 | 0.0951 | 0.1976 | 0.0776 | 0.1414 | 0.1408 | 0.1873 | 0.2320 | 0.1263 | 0.1743 | 0.1458 |
| Lx | -0.0305 | -0.0570 | -0.0850 | -0.0787 | -0.0709 | -0.0632 | -0.1049 | -0.0024 | -0.1224 | -0.0586 | -0.0592 | -0.0127 | 0.0320 | -0.0737 | -0.0257 | -0.0542 |
| L | -0.010% -0.010% | -0.010% -0.010% | -0.011% -0.011% | -0.010% -0.010% | -0.009% -0.009% | -0.011% -0.011% | -0.010% -0.010% | -0.010% -0.010% | -0.009% -0.009% | -0.010% -0.010% | -0.011% -0.011% | -0.010% -0.010% | -0.010% -0.010% | -0.009% -0.009% | -0.009% -0.010% | -0.010% |
| 14 | 0.1687 | 0.1423 | 0.1144 | 0.1207 | 0.1283 | 0.1364 | 0.0947 | 0.1971 | 0.0770 | 0.1408 | 0.1405 | 0.1870 | 0.2315 | 0.1263 | 0.1737 | 0.1453 |
| Lx | -0.0313 | -0.0577 | -0.0856 | -0.0793 | -0.0717 | -0.0636 | -0.1053 | -0.0029 | -0.123 | -0.0592 | -0.0595 | -0.0130 | 0.0315 | -0.0737 | -0.0263 | -0.0547 |
| L | -0.011% -0.010% | -0.010% -0.011% | -0.011% -0.011% | -0.010% -0.010% | -0.010% -0.010% | -0.011% -0.011% | -0.010% -0.010% | -0.011% -0.011% | -0.010% -0.010% | -0.011% -0.011% | -0.011% -0.011% | -0.010% -0.010% | -0.010% -0.010% | -0.009% -0.010% | -0.010% -0.010% | -0.010% |
| 21 | 0.1688 | 0.1424 | 0.1143 | 0.1204 | 0.1282 | 0.1363 | 0.0946 | 0.1968 | 0.0768 | 0.1405 | 0.1403 | 0.1867 | 0.2312 | 0.1255 | 0.1734 | 0.1451 |
| Lx | -0.0312 | -0.0576 | -0.0857 | -0.0796 | -0.0718 | -0.0637 | -0.1054 | -0.0032 | -0.1232 | -0.0595 | -0.0597 | -0.0133 | 0.0312 | -0.0745 | -0.0266 | -0.0549 |
| L | -0.011% -0.010% | -0.010% -0.011% | -0.011% -0.011% | -0.010% -0.010% | -0.010% -0.010% | -0.011% -0.011% | -0.010% -0.010% | -0.011% -0.011% | -0.010% -0.010% | -0.011% -0.011% | -0.011% -0.011% | -0.010% -0.010% | -0.011% -0.011% | -0.010% -0.010% | -0.010% -0.011% | -0.011% |
| 28 | 0.1683 | 0.1420 | 0.1139 | 0.1200 | 0.1278 | 0.1360 | 0.0944 | 0.1967 | 0.0766 | 0.1403 | 0.1405 | 0.1869 | 0.2314 | 0.1257 | 0.1732 | 0.1449 |
| Lx | -0.0317 | -0.0580 | -0.0861 | -0.0800 | -0.0722 | -0.0640 | -0.1056 | -0.0033 | -0.1234 | -0.0597 | -0.0595 | -0.0131 | 0.0314 | -0.0743 | -0.0268 | -0.0551 |
| L | -0.011% -0.011% | -0.011% -0.011% | -0.012% -0.012% | -0.012% -0.012% | -0.011% -0.011% | -0.011% -0.011% | -0.010% -0.010% | -0.011% -0.011% | -0.010% -0.010% | -0.011% -0.011% | -0.011% -0.011% | -0.010% -0.010% | -0.011% -0.011% | -0.010% -0.010% | -0.010% -0.011% | -0.011% |
| 120 | 0.1672 | 0.1410 | 0.1127 | 0.1188 | 0.1266 | 0.1349 | 0.0936 | 0.1958 | 0.0756 | 0.1392 | 0.1395 | 0.1860 | 0.2303 | 0.1247 | 0.1721 | 0.1439 |
| Lx | -0.0328 | -0.0590 | -0.0873 | -0.0812 | -0.0734 | -0.0651 | -0.1064 | -0.0042 | -0.1244 | -0.0608 | -0.0605 | -0.0140 | 0.0303 | -0.0753 | -0.0279 | -0.0561 |
| L | -0.012% -0.012% | -0.012% -0.013% | -0.013% -0.013% | -0.013% -0.012% | -0.012% -0.012% | -0.012% -0.012% | -0.011% -0.011% | -0.012% -0.012% | -0.011% -0.011% | -0.012% -0.012% | -0.012% -0.012% | -0.011% -0.011% | -0.012% -0.012% | -0.011% -0.011% | -0.011% -0.012% | -0.012% |
| total | -0.012% | -0.012% | -0.013% | -0.013% | -0.012% | -0.012% | -0.011% | -0.012% | -0.011% | -0.012% | -0.012% | -0.011% | -0.012% | -0.011% | -0.011% | -0.012% |
| | 0.0122 | 0.0117 | 0.0126 | 0.0133 | 0.0117 | 0.0124 | 0.0111 | 0.0120 | 0.0112 | 0.0122 | 0.0120 | 0.0109 | 0.0116 | 0.0107 | 0.0113 | 0.0115 |

Average Length Change 120 Day Period = -0.0695

Average % Shrinkage 120 Day Period = -0.012%

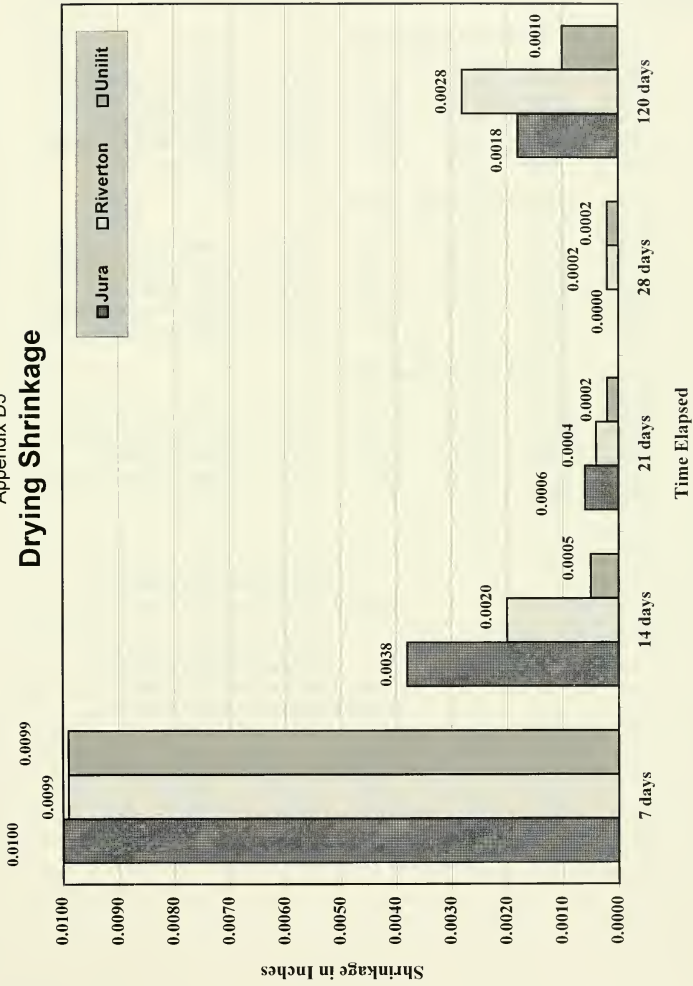
*Measurements in thousandths of an inch

DRYING SHRINKAGE AVERAGES

| Day | Jura | Riverton | Unilit | Average |
|--------------|---------|----------|---------|---------|
| 3 | 0.1672 | 0.1661 | 0.1557 | 0.1630 |
| Li | -0.0382 | -0.0339 | -0.0443 | -0.0388 |
| 7 | 0.1572 | 0.1562 | 0.1458 | 0.1531 |
| Lx | -0.0428 | -0.0438 | -0.0542 | -0.0469 |
| L | -0.010% | -0.010% | -0.010% | -0.010% |
| 14 | 0.1534 | 0.1542 | 0.1453 | 0.1510 |
| Lx | -0.0466 | -0.0458 | -0.0547 | -0.0490 |
| L | -0.014% | -0.012% | -0.010% | -0.012% |
| 21 | 0.1528 | 0.1538 | 0.1451 | 0.1506 |
| Lx | -0.0472 | -0.0462 | -0.0549 | -0.0494 |
| L | -0.014% | -0.012% | -0.011% | -0.012% |
| 28 | 0.1528 | 0.1536 | 0.1449 | 0.1504 |
| Lx | -0.0472 | -0.0464 | -0.0551 | -0.0496 |
| L | -0.014% | -0.012% | -0.011% | -0.012% |
| 120 | 0.1510 | 0.1508 | 0.1439 | 0.1486 |
| Lx | -0.0490 | -0.0492 | -0.0561 | -0.0514 |
| L | -0.016% | -0.015% | -0.012% | -0.014% |
| total change | -0.016% | -0.015% | -0.012% | -0.014% |
| | 0.0162 | 0.0152 | 0.0115 | 0.0143 |

*Measurements to 0.0001 of an inch

Drying Shrinkage



Appendix E

ABSORPTION & BULK SPECIFIC GRAVITY

ASTM C -97 Standard Test Method for Absorption and Bulk Specific Gravity of Dimension Stone

Jura Hydraulic Lime Mortar

| | 1 | 2 | 3 | 4 | Avg. 1-4 |
|---|--------|--------|--------|--------|----------|
| Dry specimen weight in g (A) | 274.2 | 274.6 | 274.7 | 272.0 | 273.88 |
| Saturated specimen, in g (B) | 303.1 | 303.2 | 303.5 | 301.5 | 302.83 |
| Absorption, Weight % | 10.50% | 10.40% | 10.50% | 10.80% | 10.60% |
| Soaked specimen in H ₂ O, in g | 169.7 | 169.9 | 170.0 | 168.8 | 169.6 |
| Bulk specific gravity | 2.06 | 2.06 | 2.06 | 2.05 | 2.06 |

Riverton Hydraulic Lime Mortar

| | 1 | 2 | 3 | 4 | Avg. 1-4 |
|---|-------|-------|-------|-------|----------|
| Dry specimen weight in g (A) | 261.5 | 261.6 | 258.2 | 261.6 | 260.73 |
| Saturated specimen, in g (B) | 286.9 | 287.3 | 283.7 | 286.7 | 286.15 |
| Absorption, Weight % | 9.70% | 9.80% | 9.90% | 9.60% | 9.80% |
| Soaked specimen in H ₂ O, in g | 155.7 | 155.5 | 152.6 | 155.2 | 154.75 |
| Bulk specific gravity | 1.99 | 1.98 | 1.97 | 1.99 | 1.98 |

Unilit Hydraulic Lime Mortar

| | 1 | 2 | 3 | 4 | Avg. 1-4 |
|---|-------|-------|-------|-------|----------|
| Dry specimen weight in g (A) | 276.5 | 275.3 | 277.8 | 276.5 | 276.53 |
| Saturated specimen, in g (B) | 303.4 | 302.1 | 304.6 | 303.2 | 303.33 |
| Absorption, Weight % | 9.70% | 9.70% | 9.60% | 9.70% | 9.70% |
| Soaked specimen in H ₂ O, in g | 171.0 | 170.0 | 171.8 | 171.3 | 171.03 |
| Bulk specific gravity | 2.09 | 2.08 | 2.09 | 2.10 | 2.09 |

Absorption, weight % = $[(B-A)/A] \times 100$

A = weight of the dried specimen

B = weight of the specimen after immersion

Bulk specific gravity = $A/(B-C)$

A = weight of the dried specimen

B = weight of the specimen after immersion

C = weight of soaked specimen in water

Appendix F

SALT CRYSTALLIZATION

Sample Weight Change in Grams

| Jura | cycle | sample 1 | sample 2 | sample 3 | sample 4 | average weight | avg. wt. change |
|------|-------|----------|----------|----------|----------|----------------|-----------------|
| | 1 | 271.3 | 272.8 | 271.9 | 271.8 | 272.0 | - |
| | 2 | 276.3 | 279.2 | 278.2 | 276.9 | 277.7 | 5.7 |
| | 3 | 281.2 | 281.5 | 283.1 | 283.5 | 282.3 | 4.7 |
| | 4 | 286.3 | 287.9 | 287.9 | 287.7 | 287.5 | 5.1 |
| | 5 | 281.2 | 283.4 | 284.0 | 286.8 | 283.9 | -3.6 |
| | 6 | 279.9 | 281.7 | 281.7 | 286.3 | 282.4 | -1.4 |
| | 7 | 281.2 | 282.9 | 282.0 | 282.6 | 282.2 | -0.2 |
| | 8 | 281.8 | 284.3 | 283.8 | 282.0 | 283.0 | 0.8 |
| | 9 | ~ | 285.6 | 283.4 | 280.6 | 283.2 | 0.2 |

| Riverton | | sample 1 | sample 2 | sample 3 | sample 4 | average weight | avg. wt. change |
|----------|----|----------|----------|----------|----------|----------------|-----------------|
| | 1 | 261.5 | 259.8 | 264.6 | 263.1 | 262.3 | - |
| | 2 | 266.0 | 265.2 | 269.6 | 267.8 | 267.2 | 4.9 |
| | 3 | 272.4 | 270.2 | 276.2 | 274.5 | 273.3 | 6.2 |
| | 4 | 275.5 | 274.9 | 279.6 | 277.8 | 277.0 | 3.6 |
| | 5 | 277.9 | 276.8 | 281.0 | 279.0 | 278.7 | 1.7 |
| | 6 | 277.9 | 276.4 | 280.2 | 278.1 | 278.2 | -0.5 |
| | 7 | 276.1 | 274.5 | 278.4 | 276.5 | 276.4 | -1.8 |
| | 8 | 279.0 | 276.9 | 282.3 | 278.6 | 279.2 | 2.8 |
| | 9 | 282.7 | 280.7 | 284.0 | 281.7 | 282.3 | 3.1 |
| | 10 | 280.5 | 279.1 | 284.2 | 283.1 | 281.7 | -0.5 |
| | 11 | 281.1 | 279.7 | 283.4 | 282.7 | 281.7 | 0.0 |
| | 12 | 277.7 | 262.9 | 274.3 | 269.5 | 271.1 | -10.6 |

| Unilit | | sample 1 | sample 2 | sample 3 | sample 4 | average weight | avg. wt. change |
|--------|---|----------|----------|----------|----------|----------------|-----------------|
| | 1 | 277.2 | 275.8 | 277.2 | 276.8 | 276.8 | - |
| | 2 | 280.8 | 279.8 | 281.0 | 282.0 | 280.9 | 4.1 |
| | 3 | 283.8 | 281.9 | 283.5 | 283.3 | 283.1 | 2.2 |
| | 4 | 288.6 | 287.3 | 288.0 | 289.2 | 288.3 | 5.2 |
| | 5 | 284.5 | 283.2 | 283.9 | 285.3 | 284.2 | -4.1 |
| | 6 | 283.6 | 282.2 | 282.8 | 284.2 | 283.2 | -1.0 |
| | 7 | 284.1 | 278.6 | ~ | ~ | ~ | ~ |

* Cycle consists of 24 hours of soaking in salt bath and 24 hours of drying in oven

* Italicized number indicates initial cracking

* ~ Symbolizes sample destruction

Anne & Jerome Fisher

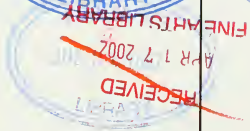
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